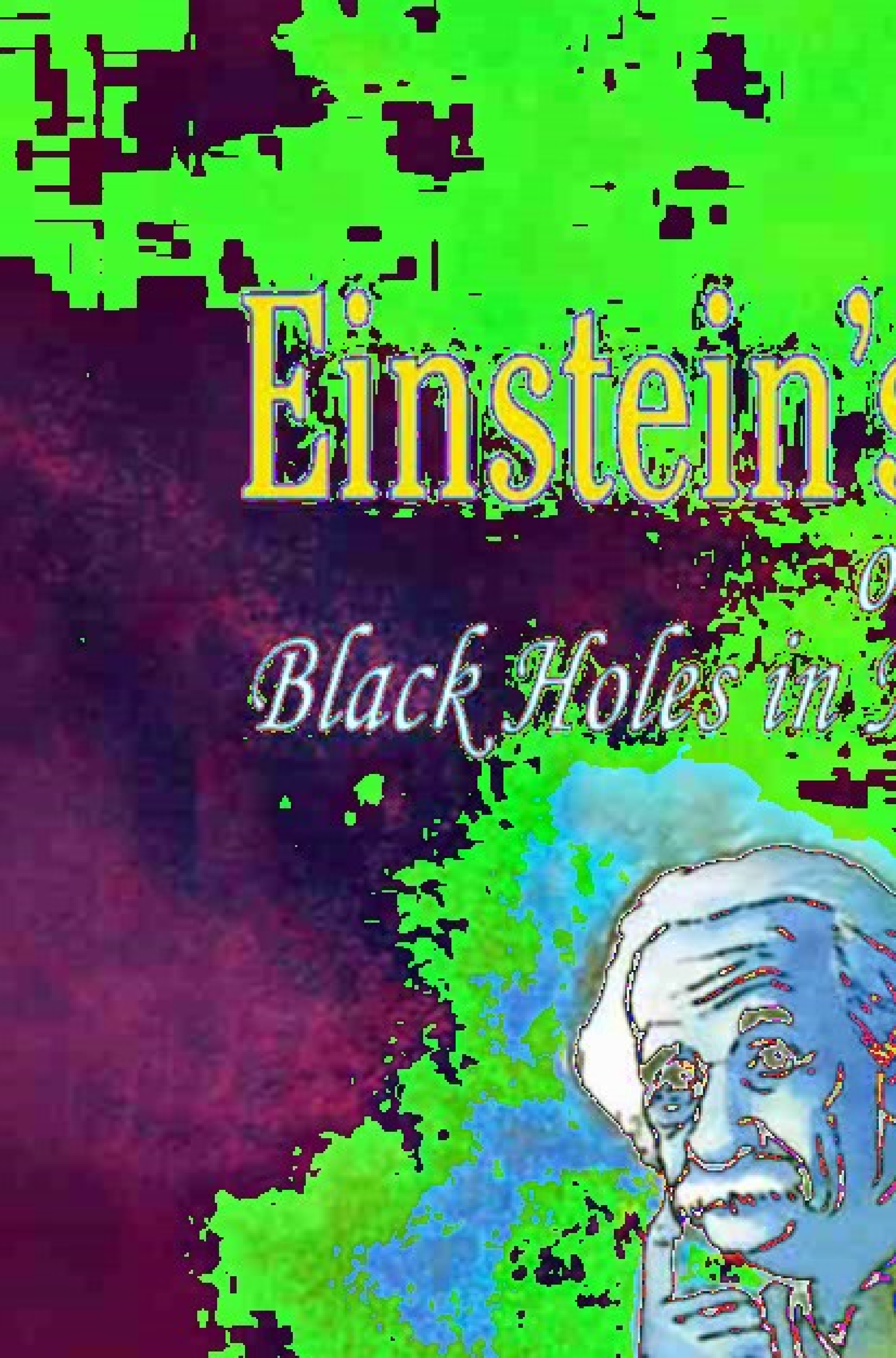
Einstein's
Black Holes in

EINSTEIN’S ENIGMA

or

Black Holes in My Bubble Bath

C. V. Vishveshwara

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To the memory of my parents

My father C. K. Venkata Ramayya
Writer, scholar, orator
And
My mother K. Venkatasubbamma
Who supported my father and took care of us all

CONTENTS

Chapter 1

THE BATHTUB

I love my bathtub. To all appearances, there is nothing special about it except that it is rather small. It is an old fashioned bathtub made of enamelled metal, discoloured at several places with spidery patterns showing up where the enamel has cracked. But, there is magic in my bathtub. It has strange, unusual powers. I shall tell you all about it in good time, if you will bear with me. First let me recount how I came to acquire this treasure of mine, which was an extraordinary event in itself.

It happened a few days ago. I woke up late and lazed around having worked all through the previous night. What kind of work do I do? You may ask. Well, I am a FLOP, a Free Lance Organiser of Proposals, that is. You would be surprised at the number of people who find it hard to write up projects and proposals that enable them to sell their ideas. I help them. For a fee of course! I arrange facts and figures, make up charts and tables, generate graphs and diagrams, and tie up the whole caboodle in pink ribbon ready for consumption. I am the systematiser of the disorganised and the voice of the inarticulate. Do you have a proposal for a genetically engineered purple cow with green spots that gives claret instead of milk and lays dinosaur eggs? No problem. By the time I am done with it, any funding agency would be eating out of the cow's hoofs. As a matter of fact, on the night before the fateful day, I was working on a patent application for a high-tech toothbrush. The computerised handle of the toothbrush contains toothpaste that is released in accurately measured, minute quantities. The bristles are the sensors of a miniature ultra-sound seismograph that scans the cavities and generates colour-coded pictures on the back of the brush head, which serves as a video screen. The data are transmitted to the user's dentist by e-mail, fax, and telepathy. The treatment can be received instantaneously, if it is in the action-at-a-distance form like *Reiki*, which invokes the universal life-force. Does this gadget work? What does it matter?

It is ideas that rule the world, even if they do not work. The toothbrush idea worked for me all right, since I had collected my fee in advance.

To continue. On the day that I consider to be the most important one in my life, I shaved, showered and got ready to go out. I live on the third floor of an old apartment building. The roof-terrace above me is, by arrangement with my landlord, exclusively my domain. There I can do whatever I please. If I so wished, I could freely sun bathe in the nude, stargaze with the naked eye or just let the fog swirl around me. Graduate students, who study in the nearby university, occupy apartments other than mine. Descending the stairs is like making a culinary tour around the world. A sensitive olfactory analysis of the smells emanating from different apartments would reveal the cuisine of various nationalities. Such as the Chinese, Indian, Spanish and so on, all characterised by the spices of the respective regions, like ajinomoto, asafoetida, and aceite de oliva virge. I am unable to identify the smell coming out of one particular apartment. For all I know, a bunch of students from the Arctic may be living in that apartment, frying algae in whale fat for their food. The ground floor is filled with the fragrance of various perfumes. Some girls live there. Probably, they never cook, managing to subsist on – dates.

As I walked down from my apartment house to the street corner, Fernando and his wife Maria, who own a small store that sells groceries and household goods, greeted me. When they are not busy, Fernando and Maria relax on the sidewalk in their lounge chairs outside their store, often sipping beer or wine and chatting away. Their eleven-year old daughter Falicia keeps a menagerie of animals – a cat, a rabbit, a turtle, and small animals of different kinds. I am expected to say hello to at least one of them whenever I meet Falicia. This time it was Macho the turtle. The turtle lifted one eyelid, looked at me dolefully and made a sound that resembled a deep sigh. ‘Off to Bruno’s as usual, *Señor* Alfie?’ called out Fernando. Ah, that is my name, Alfie for Alfonso L. Sabio. I nodded, smiled and moved on.

Bruno’s, as it is popularly known, is *Benvenuto* the cosy little Italian restaurant. Bruno Beltrametti is its owner, chef, and the headwaiter all rolled into one. The tables are neatly arranged, covered with beige tablecloths embellished with intricate designs in maroon. Placed on each of them is a cylindrical flower vase made of solid Venetian glass accommodating a single flower. Bruno plays soothing classical and folk music in the background and sometimes, if persuaded, sings arias from his favourite operas. Most importantly, he supplies stacks of paper napkins that are freely used by the university people who frequent the restaurant. Physicists write formulas on them, biologists doodle molecular structures, artists make sketches, while mathematicians just twist them around as they think their abstract mathematical thoughts – or at least that is what they claim.

As I munched on the toasted cheese that came with my pasta and sipped my second glass of Bruno's delicate wine, in walked George Gallagher. Blew in like a whirlwind I should say. George works in theoretical astrophysics. He is one of the university people I have met at Bruno's. Over the years, a close and warm friendship has grown between the two of us.

George slumped into the chair next to mine and ordered a Sicilian and a large beer. A Sicilian, if you have never tried it, is a small, thick, square pizza. According to George, his colleagues at the university are fond of Sicilians, because, like the dish, they are all square and thick even though they claim to be liberal intellectuals. Of course George is an exception. Bruno dislikes the Sicilian immensely. 'What can I do, I have to make a living, no? So I prepare it,' he says. Probably no one in Sicily has ever heard of this dish. If you insisted that it originated in Sicily, the *Cosa Nostra* might rub you out.

'Oh, Alfie my boy, I am tired, tired, tired,' sighed George as he took a big gulp of his beer. 'It is all because of old Albert Einstein you know.'

'Why, what has he done to you now?'

'You see, in 1905, sitting in his patent office in Berne, he did wonders. He explained Brownian motion, the feverish motion of molecules in a liquid. He explained the photoelectric effect, electrons streaming out of some metals when light was shone on them. He gave the world his special theory of relativity. Which completely changed the way we look at nature. Space and time became relative quantities. So did mass. It was a revolution. Drum rolls, cannons firing, the whole works. Bam, bam! That was good enough. Did Einstein stop there? No, the old fox goes on and formulates his general theory of relativity. A brand new theory of gravitation totally different from that of good old Isaac Newton. What happens? The new theory predicts all sorts of crazy things like black holes, gravitational radiation, the expanding universe and what not. And I have to deal with all this in my old age. Bruno, another Sicilian and a large beer please. And Bruno, please stop grimacing like that. It takes away my appetite.'

'Go on George,' I patted his hand. 'Pour it all out: I shall drown your sorrows in alcohol for you.'

'All right, once we theoreticians could dream up things unhampered by reality. Reality, my friend, is a redundant nuisance if you ask me. But now, observations have caught up with us. We have to account for all sorts of bizarre things happening up there in the sky. Just yesterday, we learnt about some extraordinary phenomenon occurring in our own galaxy. I think two binary systems, each containing a black hole, are merging together. Dealing with just one black hole, swallowing up matter and energy is difficult. Two make it extremely hard. But handling two binaries each containing a black hole! Heaven help me, it is almost impossible. We shall crack it anyway. Alfie, you don't look too happy. What is the matter, my boy?'

'Let me confess. I feel a bit uncomfortable with all this black-hole talk.'

'Why? Black holes are beautiful you know!'

'I don't doubt that. But, I hear all these words – black holes, binaries, mergers and what not. You'll have to explain everything to me from scratch, George, so I am able to understand what is going on. Then I can really appreciate your problems.'

'Fair enough. All right, next time we meet I'll begin my private lessons tailored to suit you. Provided the drinks are on you,' said George. And then he added, 'Seriously, Alfie, would you like me to talk to you for an hour or so and give you just an overview of black holes? Or should we have several sessions so I can deal with the subject in some detail complete with all the background material and do justice to it? The choice is yours.'

'No doubt about it, George, let us meet as many times as you wish. I'm ready for a detailed exposition. Would you be using mathematics though? Not that I am afraid of it.'

'Very well then, I'll write down some very simple mathematical expressions, which even a high-school kid can understand. That makes things much more precise, you know. Of course, they are not absolutely essential for understanding black-hole physics. But, they would help. And we can draw enough diagrams to illustrate whatever we discuss. What do you say?'

'Sounds great,' I said enthusiastically.

'I have to rush now, Alfie. My students are running a monstrous computer programme. And I have to be there all night to give them moral support.'

'In other words: To breathe down their necks. George, don't be too hard on those poor boys.'

'Two boys and one girl to be precise. I will be no harder on them than on myself, I promise. Bye, Alfie. Ciao, Bruno.'

George swept out like a tornado. All this heady talk and the somewhat generous consumption of wine had made me a bit tipsy. I wished Bruno good night and started on my homeward journey.

Just before reaching the street on which I live, there is a blind alley. Along the short stretch of this passageway there are a few empty derelict buildings and a couple of warehouses. There are no streetlights. At night it is dark and dismal here. But that night, there seemed to be some signs of life within one of the buildings. A diffuse shaft of light emerged from one of the windows and dissipated itself in the surrounding fog. This was a bit surprising, because this building has been sealed off for quite some time now. Even more intriguing was the fact that there was a sign above the door, which read *Al's All-in-One Store*. There were several other signs as well listing an assortment of items available within and a big one announcing *Bathtubs for Half Price*! I had never noticed any of this before. Quite curious about this new place, I pushed open the door, which happened to be unlocked, and entered.

The place was crammed with a chaotic variety of merchandise. There was no one in sight. Rather suddenly and instinctively, I felt a presence close to me. Sure enough, a man had appeared at my elbow, presumably the storekeeper. I was riveted by his eyes looking straight at me. Eyes that were gentle and kind, yet with a mischievous twinkle in them. Time had etched a network of lines on his calm face framed by a halo of white hair.

'I am Al, at your service,' he said with a warm, friendly smile. 'So you have come for your bathtub, *ja*?'

He spoke softly but with a thick accent. I could not place it. German? Swiss? Or perhaps it was one of those accents that belonged everywhere and nowhere.

I had entered the place with no intention of buying anything whatsoever. But this stranger had assumed that I had come to buy a bathtub of all things. Before I could even think about this turn of events, Al spoke up.

'*Wunderbar!* Follow me please, if you will, *mein lieber Herr*.' He gestured with his head, his long, unruly hair waving in the air, to show me the way. He had a quiet way of walking almost like a slow dance movement.

As Al led the way, the room seemed to expand and turn into a large gallery that held an assortment of bathtubs of different sizes, shapes and colours.

'Ah, you are surprised,' said Al with amusement. 'Yes, we have a magnificent collection of bathtubs. Many of them have great historical value. Obviously, they are not for sale. Here, let me show you some of them. Look at this one. It comes from ancient Egypt. Belonged to some queen or the other they say. Nefertiti perhaps. Maybe Cleopatra. Let's assume it was once Cleopatra's since she is better known. Legend and fantasy are as important as reality, sir. Or possibly more. But look at it. Is it just a bathtub? No, sir, it is a magnificent piece of art! What is more, its design and decoration reflect the cosmic order that the ancient Egyptians once believed in.

According to the Egyptian cosmic myth, Al went on to explain, the sky goddess Nut, decked with shining stars, arches over her reclining husband Seb, the earth god, while their offspring Shu, who controls the winds, kneels between them. The sun, in the form of Amon-Ra, god of gods, sails in his divine barge along Nut's body. Each night he dies and enters Amenti, the nether world, to be broken up and scattered in a thousand sparks that turn into the stars. At dawn he is reborn to repeat the perpetual cycle of birth and death.

The bathtub, shaped like the sun's barge, was enormous. It was made of black marble covered with innumerable semiprecious stones of different kinds. One half of it was inlaid with flakes of turquoise and lapis lazuli to simulate the blue sky. In the middle was the brilliant sun fashioned out of a mixture of gold and silver. The blue sky turned gradually into yellow and red twilight created by shimmering pieces of amber and garnet. Finally the night sky was depicted by the dark background of black marble itself studded with a variety of sparkling white stones including a spray of small diamonds. An opal moon shone with a soft glow. The effect, to say the least, was stunning. This bathtub, which was supposed to have belonged to Cleopatra long ago, reminded me of her barge as described by Shakespeare:

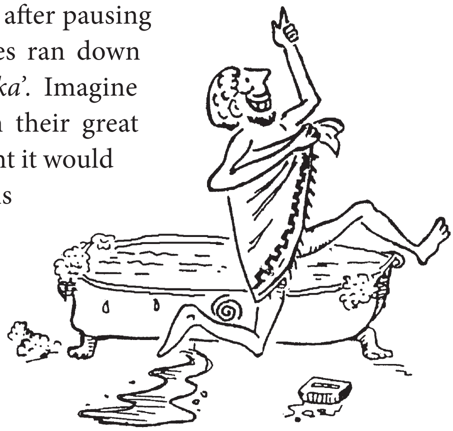
The barge she sat in, like a burnish'd throne,
Burn'd on the water; the poop was beaten gold,
Purple the sails, and so perfumed, that
The winds were love-sick with them; the oars were silver,
Which to the tune of flutes kept stroke, and made
The water which they beat to follow faster,
As amorous of their strokes. For her own person,
It beggar'd all description.

Lovely, don't you agree? At this point, I must warn you of my phenomenal memory for anything and everything I read. I can reel off short quotations, recite long passages and supply you with an abundance of unbelievable trivia at the drop of a hat. And I often make good use of my rare gift, as you will see. But let me continue with my story.

'Here is my favourite one, *mein lieber Herr*,' said Al as he patted the next bathtub. It had been carved out of white marble, simple and elegant, in the shape of a perfect ellipse. On one side was engraved the picture of a pole balanced on a conical peg, while on the other there was a spiral.

'The owner of the bathtub discovered the spiral you see engraved on it. He claimed that, if he were to be given a long enough lever and a place to stand in space, he could move the earth,' Al said. And then he jubilantly announced, 'His name was Archimedes'

'From this very bathtub', Al continued after pausing dramatically for a moment, 'Archimedes ran down the street, stark naked, shouting '*Eureka*'. Imagine our scientists following his example in their great haste to publish their results! What a sight it would be!' Al bellowed with laughter, tears in his eyes. The contrast between his soft speech and his ringing laughter, which echoed from wall to wall, was enormous. I was totally unprepared for this roaring, booming, friendly, all-enveloping laughter.



Al's expression turned serious as he led me to the third bathtub. It was in the shape of a crude rectangular box and the material used was humble sandstone, chipped at many places. It was unadorned and looked more like a coffin rather than a bathtub. Lying inside was a badly decayed plank smudged with patches of black.

'Here is a gory one that was much used by its former owner Jean Paul Marat, one of the leaders of the French Revolution. As the story goes, he had contracted some horrible skin ailment when he was hiding in the sewers of Paris and had to soak himself constantly in lukewarm medicated water. He used that plank lying there for writing. A woman named Charlotte Corday stabbed him to death during one of his soaking sessions. What a way to go! You must have seen the painting entitled *Marat*, by the French artist Jacques Louis David, depicting Marat's death. I am told that, if you look carefully, you may still discover some faint bloodstains in this bathtub. Gives you the creeps.' Al seemed to shiver at the thought. 'Well, there are many other historical specimens. But let us take a look at the one you have come for. Pardon me, the small black box over there is not a bathtub. It is my violin case,' Al roared with laughter.

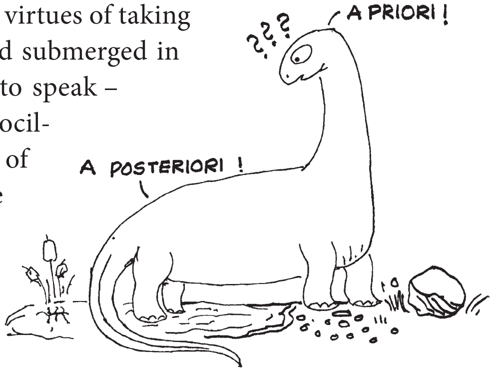
'As you know, sir,' continued Al, filling his pipe and lighting it as he led the way. 'Taking a bath is an extremely important part of one's life. Could anything else offer the blissful state of prenatal insouciance as when you lie soaking yourself in warm water, eyes closed and preferably sucking your thumb? Throw in some bath salts containing special ingredients including specific metals. Then millions of molecules in frenzied Brownian motion will massage your muscles and photoelectrons will stimulate your cells. Time will stand still. Somebody should take out a patent on this invention, the Brownian Photoelectric Bathtub. What do you think?'

Momentarily, his eyes became distant and dreamy as though he had been transported to another place, another time. 'Patents, Brownian motion, photoelectrons, time slowing down. Oh yes, those were the days!' he whispered to himself. Returning from his reverie, he went on, 'Where were we? Oh yes, the virtues of taking a bath. You know, sir, a whole species could be wiped out for the lack of bathing. Take for instance the dinosaurs. I vaguely remember a verse written in the early nineteen hundreds that described dinosaurs and their two brains. That verse I think is quite relevant to what we are talking about. I am sure you must have read it too.'

As a matter of fact, I had read the poem Al had in mind. One Bert Taylor of the *Chicago Tribune* had written it in 1912. I had long forgotten it, but my unfailing memory brought it back to my mind. The lines about the dinosaur's purported two brains are as follows:

The creature had two sets of brains.
One in his head, the usual place,
The other in his spinal base.
So that he could reason a priori,
As well as a posteriori.

The entire poem is quite interesting. I hope you will read it some time. For the moment, let me go on with what Al was telling me.



Al went on with his discourse on the virtues of taking a bath. 'As long as the dinosaurs stayed submerged in water – taking long, healthy baths so to speak – the bottom brain was kept lulled into docility. But when the dinosaurs crawled out of water and became land animals, the lower brain started competing with the upper one. *A priori* and *a posteriori* got mixed up and the species became extinct. Humans do not have this problem mercifully, since they are not equipped with a brain at the base of their spines, although many behave as if they did. Well, I am told that modern findings do not support the hypothesis that the dinosaurs had two brains. What a pity, a beautiful hypothesis dashed against the hard rock of fact. Anyway, allow me to let you in on a secret. Personally, I hate baths myself. That follows in the tradition of the great Kepler who bathed only once in his entire lifetime. That too was at the insistence of his wife and against his own better judgement. It nearly killed him. So, I try to avoid taking a bath although I extol its virtues. As you very well know, sir, there is nothing nobler than to preach what one does not practice.'

Al bent down to tie his shoelace. His shoes were scuffed and he wore no socks beneath his rumpled trousers. Straightening up as he smoothened the sweatshirt he was wearing, he exclaimed, 'Ah, now for your bathtub!' With a flourish, Al pulled off the tattered cloth that covered the bathtub. I could not believe my eyes. This bathtub, as he called it, was nothing more than a kitchen sink! How could anyone but a midget get into it was beyond my comprehension.

'You are obviously surprised at the modest dimensions of the bathtub. Half price, half size!' laughed Al. 'But take my word for it. You will find no difficulty in getting into your bathtub. What is more important is the fact that the bathtub is a magical one. It is filled with myth, math, science, philosophy, art, literature, and above all dreams; not to mention your bath water.

The so-called bathtub came with a kit on which was written *Five Easy Steps to Install Your Bathtub*.

'Oh, yes, it is child's play to install your bathtub,' said Al. 'I am going to wrap it up in brown paper, and tie it with string. There you are, all yours.'

There was a problem though. Old-fashioned kitchen sinks, like this one, could be quite heavy. How was I going to carry it home?

'How are you going to carry it?' Al seemed to read my mind. 'Not to worry! We will have it delivered to your doorstep in no time. Oh, I almost forgot. Along with the bathtub, you get a free sample of our special bubble-bath additive.'

He produced a plastic bag filled with perfectly spherical black beads. They were black in a peculiar manner, reflecting no light at all, but quite pretty in a way. He walked me to the door and held it open for me.

'Rest assured that your newly acquired possession will give you wondrous moments you could never have imagined. Goodbye now,' said Al. As I watched him, I wondered whether I had met him before. No, no, that was impossible. Did he closely resemble someone whose description I had read before? My mind seemed to have become fuzzy and I was confused. I caught myself meandering through the maze of my memories as I realized that Al was regarding me with a mysterious, knowing smile. As I was about to leave, Al said gently, 'We shall meet again soon enough, my friend.'

Slowly I started walking home. Before turning the corner, I looked back. The alley was plunged in darkness and there was no longer any light in the shop. Had I been dreaming? The shop, the shopkeeper and everything that had happened, was it all my imagination? The whole episode was a bit scary.

Fernando and Maria were still in their lounge chairs. They had closed their shop and were having a beer before retiring.

'Want to have a sip with us, *Señor* Alfie?' Fernando asked.

'Thanks Fernando. Some other time. I am a little tired.'

'Tired? You look more like, let me see, dazed I would say. What have you been up to, *Señor* Alfie?' Fernando grinned slyly.

'Oh, I have been browsing around a bit in this quaint little store I found. That's all, Fernando,' I replied.

'What store is that?'

'*Al's All-in-One Store*. You must know it.'

'Never heard of it. Where is it?'

'At the beginning of the blind alley behind our street. Second shop on the right you know.'

'Are you sure? There's no such shop. I was there just this afternoon. That place has been boarded up for long time now. Well, what more can I say?' Fernando looked at me searchingly. But before Fernando could fire off more questions, I said good night to the two of them, who seemed to be quite curious, and left.

I trudged up the stairs to my apartment, tired and confused. Once again I wondered whether I had imagined the whole thing about Al and his store. I stopped short at the door of my apartment. There it was! Neatly arranged in front of my door was the big package wrapped in brown paper, tied around with string. I was stupefied. My bathtub delivered to my doorstep as Al had promised! I quickly unlocked the door and carried the bathtub inside. Surprisingly, it felt quite light. I went straight into my bathroom and fixed the little bathtub in five easy steps as instructed by the accompanying kit. The magic moment had arrived. I filled it with hot water, stirred in half a spoonful of the bubble bath mixture and gingerly got in. To my amazement, I was able to fit into the bathtub quite comfortably. Had the bathtub expanded? Had I shrunk? It mattered little. The bubble bath was unbelievably soothing. Not just physically. The vapours rising from the bath water seemed to seep into my mind and turn it into a soft, smooth fluid in which thoughts, imagination, and awareness of the external world mingled in a flowing stream. Countless bubbles surrounded me now. Transparent, multicoloured spheres that glistened and trembled. Within each bubble, I could see a dark speck, once again a minute, perfect sphere. Each black speck appeared to grow a little, as it absorbed the vapour in its immediate vicinity. Here and there, bubbles would combine and become one, while the black specks too coalesced. As they did, they seemed to become warmer. Some bubbles burst when the black specks within them evaporated and disappeared. Slowly, words I had heard in the evening came to my mind. Black holes, swallowing up matter and energy, merging together! Was this happening in my own bathtub? Or was I imagining things yet again?

The bubbles were swirling all around me massaging my body. There was a large concentration of them near my feet. They were gently tugging at me. As I luxuriated in this fantastic bubble bath, my eyes grew heavy and I drifted into a supremely blissful slumber.

Chapter 2

THE STELLAR BED

When I entered Bruno's, I saw that George was already there, waiting for me at our favourite table. George is in his fifties, thickset but not fat, with an incipient paunch, hair turning grey and thinning. Beneath his bushy eyebrows, he wears thick-rimmed glasses that keep sliding down his nose, requiring him to keep pushing them up constantly. Invariably he wears a jacket, not for the sake of appearance he says, but to stuff the pockets with important papers - each pocket reserved for a particular type of document. In other words, his jacket is his mobile filing cabinet. All in all, George looks quite distinguished and can easily pass for a professor, which he is.

'Bruno,' George called out after greeting me warmly. 'Let us have your most expensive wine, please. Alfie is going to pay for it. Fee for the lessons I will be giving him.'

'I don't know about expensive wine,' replied Bruno. 'But I got some excellent wine straight from Frascati. Something they supply to the Italian President himself. No labels. Want to try?'

'Do you have to ask, Bruno? What do we eat?'

'What you eat must match what you drink,' Bruno said solemnly. 'Just like what you drink must match what you eat. It is like happy marriage.'

'And the consummation lies in its consumption. Right, Bruno?' I added.

'So, I make you my special Zuppa Marinara. My own recipe. Not on the menu.'

'Oh, no, Bruno,' protested George. 'I am not in a mood for any fish soup.'

'My Zuppa is not your watery soup, you know,' Bruno explained patiently. 'It is fresh shellfish cooked in sauce of Marsala wine. Served on a bed of thick bread soaking up the sauce slowly. A side dish of pasta with herbs. *Perfetto*!'

'Bruno, the Greeks said that one of their ideals was a sound mind in a sound body,' I commented. 'But you are giving us sound minds in round bodies!'

'What do I know about the Greeks? I am from a Latin country,' Bruno shrugged.

'Actually, Bruno, the person who mentions this ideal was not a Greek at all,' I explained. 'He was a Roman, so your countryman, you see. He was the satirical poet Juvenal, who lived in the second century AD. And he wrote in Latin, *mens sana in corpore sano*, a sound mind in a sound body. But you give us *mens sana in corpore rotundo*, a sound mind in a round body!'

Bruno shook his head, looking at me as if I had gone completely out of my mind and walked away.

'Come to think of it, Alfie, the Greeks' ideal of roundness went a long way,' remarked George. 'That concept entered their astronomy too, you know. Circle and sphere, the perfect figures in two and three dimensions. That is why for centuries the orbits of the planets were assumed to be circles until Kepler showed that they were ellipses.'

'Let me add a bit more to this roundness business, George,' I offered. 'You know what Xenophanes, in the Sixth Century BC, thought? He claimed that God, being perfect, had to be spherical in shape! According to Aristotle, Xenophanes wrote that the *universal homogeneity of God implies that he has the shape of a sphere. And because he is uniformly the same and round as a ball, thus he is neither limited nor unlimited, neither in rest nor in motion*. But some people made fun of this notion, you know. They parodied the word *apotheosis* or deification as *apokolokinthiosis* or pumpkinification! The two Greek words sound somewhat similar, don't they?'

'Obesity is close to divinity then,' George chuckled.

'Indeed. Let us eat and get fat,' I said.

'Well, let us forget the spherical God for a moment,' George said. 'Lots of things in nature are spherical in shape though. Take, for instance, the Solar System. The Earth is almost spherical. So are the planets. There is always some flattening due to rotation, of course. As a matter of fact, the Sun is spherical too.'

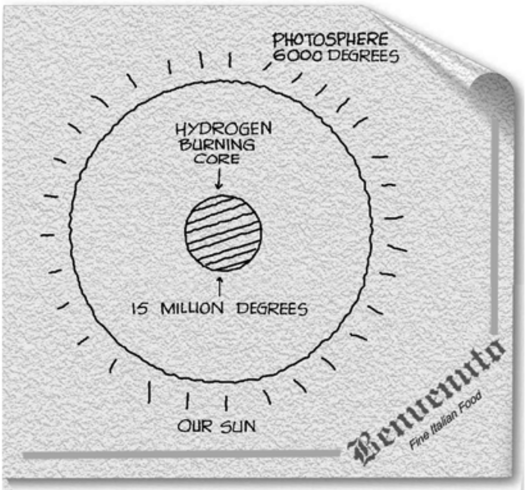
The wine had arrived. I took a sip. It was exquisite, mellow with a hint of the grapes that had undergone this unearthly transformation. George sighed with pleasure. He pulled out a paper napkin and started sketching as he described the anatomy of the Sun.

'Let me continue. The Sun is a huge ball of fire, a sphere of burning gas,' George went on. 'It is seventy-five per cent hydrogen, about twenty-four per cent helium and a small quantity of other elements. What we see of the Sun is the light from the surface, which is at a temperature of about six thousand degrees. By the way, in astronomy we always use the Kelvin scale for the temperature. I am sure you know what it is, Alfie.'

'Oh, yes. You take the centigrade or the Celsius scale, which consists of equal degrees between zero, fixed at the melting point of ice, and one hundred, fixed at the boiling point of water, at a pressure of seven hundred and sixty millimetres of mercury. To get the Kelvin scale, you add two hundred and seventy-three degrees to the Celsius temperature. So, zero on the Kelvin scale corresponds to minus two hundred and seventy-three degrees Celsius. This is known as the absolute zero temperature. How about that?'

'Amazingly accurate, Alfie,' George chuckled.

'All right, coming back to the Sun, the energy actually comes from the centre, doesn't it?'



'Exactly. Most of the mass of the Sun is concentrated around the centre, nearly ninety per cent within the inner half of its radius. The temperature at the centre is some fifteen million degrees. Horribly hot, wouldn't you say?'

'Right, an inferno too hot for even Satan.'

'The pressure is about a hundred billion times that of the Earth's atmosphere. And the density is around twelve times that of lead.'

'Are you saying that the Sun has a solid core or what?'

'Did I say that? No, sir. The temperature is so high that the electrons are ripped off the atoms. They fly around madly, leaving the nuclei shamelessly naked. The nuclei themselves streak around at a frenetic pace and come close to one another. The density and pressure are extraordinarily high. But this violently agitated mixture still behaves like a gas, you know. So, the core is not solid at all. This is the nuclear furnace where the Sun's energy is generated. We shall talk about the nuclear processes taking place here a little later. All this talk of a hot core has made me thirsty.'

George took a couple of sips and continued.

'The energy is created in the form of high-energy X-rays, or gamma rays as they are called. As this radiation travels towards the surface it is continually scattered by the matter in the Sun's interior. As a result, it keeps losing energy as it travels and becomes the visible radiation streaming out of the Sun. Can you guess how long it takes for the radiation to travel from the centre of the Sun to its surface?'

'Let me estimate rather than guess. What is the radius of the Sun?'

'About 700,000 kilometres.'

'All types of radiation travel at the speed of light, right?'

'Right.'

'The speed of light is around 300,000 kilometres per second, right?'

'Right again.'

'Divide the radius by the speed and we get the time taken by the radiation to travel from the centre of the Sun to its surface. Which is – aha – a little less than two and a half seconds. Right?'

'Brilliant. But wrong!'

'Why, George, it was trivial arithmetic?'

'Mathematically correct, Alfie, but physically wrong, I am afraid,' remarked George. 'Let me explain. You can easily walk from here to your home, a couple of kilometres away in, say, fifteen minutes. Provided you are not in an inebriated state, which is normally a wrong assumption. But then, important theories are often built on wrong assumptions anyway. Well, suppose you tried to cover the same distance downtown on New Year's Eve. It may take you an hour or more. You would be colliding with every reveller and getting jostled this way and that. That is precisely what happens to each photon of radiation trying to escape from the crowded interior. It takes the poor thing thousands or even millions of years to reach the surface. Like a weary, worn-out traveller who has lost much of his energy. After that, it is a flight of a mere eight minutes in empty space from the surface of the Sun to the Earth.'

'That is most interesting, George! I never knew that.'

'Well, not many do, I must say.'

'How does this mass of hot gas in the Sun remain a spherical globe of fire instead of simply spreading out?'

'I think you know the answer, Alfie,' commented George looking at me from above his glasses. 'The answer is gravity, of course. The self-gravity of the gas pulls it towards the centre. There is a perfect balance between this inward pull of gravity and the outward pressure of the gas. And the Sun continues to exist, retaining its size and shape.'

Bruno brought the food, Zuppa Marinara and pasta. George pried open a shell, speared the mussel along with a piece of bread soaked in the Marsala sauce and placed it in his mouth. He closed his eyes in ecstasy while Bruno looked on with satisfaction.

'You know what, Bruno?' I said to Bruno as I tasted the food. 'One of your great predecessors was Brillat-Savarin. A famous French cook who lived in the seventeenth century. You know what he said? *The discovery of a new dish does more for human happiness than the discovery of a star!* Bruno, you are proving his point admirably.'

Bruno just smiled and left.

'That perceptive observation of your French cook brings us naturally to the stars,' remarked George. 'After all, the Sun is a star too. So we might as well think of the stars in general. On a clear night, you can see a couple of thousand stars with the unaided eye. A pair of binoculars would increase this number considerably. Many of the stars are in fixed patterns.'

'I know, constellations, as the ancient Greeks called them.'

'How many of them do you know?'

'I can identify two or three. Like Orion the Hunter. In no way does it look like a hunter.'

'You are right, Alfie. The Greeks imagined their heroes, heroines, beasts, and demons in those stellar patterns. We have to imagine them too. Once you have done that, you will always remember the constellations and the stars that define them.'

'I suppose it works both ways.'

'How do you mean?'

'I mean the stars and the constellations could be remembered by associating them with mythological characters, right? In turn, those myths were immortalised through the stars that were considered to be eternal. So one's cultural heritage is preserved forever. That is why different cultures must have attached their legends to the stars – like the Chinese, Indians and Arabs for instance. Don't you agree?'

'You are absolutely right,' concurred George. 'But it is the Greek constellations that have remained popular. Of course, more constellations have been added to the list since the time of the Greeks. They couldn't see those that are visible only in the southern hemisphere, could they? There are eighty-eight constellations in all covering the entire dome of the sky. They come in handy for locating celestial objects. Even now, modern astronomers use them for this purpose all the time.'

'Stars belonging to the same constellation are in general at different distances from us, aren't they? Because they are all so far away, they tend to appear to be bunched together.'

'Yes, indeed! Distances of stars vary over a wide range. And so do their properties. Our Sun is an average, common-or-garden star. But there are stars that are heavier or lighter, bigger or smaller, brighter or dimmer compared to the Sun. They come in different colours too, depending on their surface temperatures. Hot stars are bluish. Cooler ones are red. Our own Sun is yellow in colour. When they stabilize after their formation, stars keep their respective colours for a long time.'

'Aha, with us humans it is different. Some yellow with age, while some mellow with age,' I observed.

'You are right. And needless to add, I belong to the second category,' said George. 'Well, all stars, including the Sun, have their own life cycles. Once again, just like humans. Birth. Existence. Death. Or BED for short. All life is a BED and we are the sleepers. It could be a BED of roses or a BED of thorns. It all depends upon how you make it.'

George was trying to strike a dramatic pose gazing at his wine glass held at arm's length. Like Hamlet holding Yorrick's skull. But it was rather comic. I could not suppress a smile.

'You are amused. Some people have no sense of the profound,' George admonished me and continued. 'Let us take a look at the birth of a star. In the vast spaces between the stars, there are huge clouds of gas and dust. You mentioned the constellation of Orion. The Great Nebula in the Orion is an example. You can see it beneath the belt of the Hunter with a pair of binoculars. Such gas clouds are the breeding grounds of stars. Here and there, the gases in the nebula clump together. As gravity pulls the gas in such a clump inwards, it starts condensing and grows increasingly dense. The temperature rises because of this compression, finally reaching millions of degrees. At such temperatures, nuclear reactions are triggered that produce immense amounts of energy. And a star is born.'

'How long does this initial process take?'

'The period of stellar pregnancy? For the gas cloud to shrink from a diameter of trillions of kilometres to the present size of the Sun, it would take, say, about ten million years. Give another twenty million years and the star will stabilise.'

'George, you guys studying stars and what not talk as though these big numbers are nothing. Do you really feel that way, or is it part of the showbiz jazz?'

'A bit of both I suppose,' George laughed. 'I guess you know your big numbers. A million is one followed by six zeroes, a billion nine zeroes, a trillion twelve zeroes and so on. Used to be called astronomical figures. Now they belong to economics as well with all the budget deficits and what not. And then there is the big measure of distance, the light-year.'

'I know that. It is the distance travelled by light in one year which amounts to about ten trillion kilometres.'

'I am impressed. How do you know these things?'

'Sometime ago, there was this patent application for a photon accelerator, which would speed up photons beyond their normal velocity. I know this is impossible. Light always travels with constant speed in a vacuum. But I learnt a lot about light waves, wave fronts, photons and all that. The estimated length of the accelerator was a few light-years. Let me describe how this accelerator is supposed to work.'

'Very interesting, Alfie, but no thank you. However, like the honest citizen that I am, let me earn my free drinks. So back to the stars,' said George. 'Birth, B, is over. Now we come to E, for existence. E also stands for equilibrium, the essence of existence. Nice alliteration, if you hadn't noticed. Anyway, you can exist only if you keep your balance among opposing forces. Stars are no exception. In the case of a star the outward pressure is created by the heat, which is in turn generated by the nuclear reactions going on at the centre. This is exactly balanced by the inward pull of gravity. We discussed this already, didn't we? So a star like our Sun remains in equilibrium, shining for about ten billion years. Our Sun is a middle-aged guy having spent almost half of his life span. No middle-age crisis though. A happy stable life for the next five billion years. Let us drink to that.'

'The pull of gravity I know. But what kind of nuclear reactions are we talking about?'

'That is exactly what I was going to tell you after toasting the sun.'

Having sipped his wine, George was about to wipe his mouth with the paper napkin on which he had been sketching.

'Hold it!' I exclaimed in alarm and stopped him.

'Why, what is the matter?' asked George a bit startled.

'You were about to wipe your mouth with the napkin on which you have been writing. Don't do that, George.'

'Why not?'

'For two reasons. Firstly, the ink may contain lead. You may get lead poisoning and your brain may become weak. Did you know that one of the causes of the decline and fall of the Roman Empire was lead poisoning? You won't find it in your Gibbon though. But, let me tell you, the Romans started drinking their wine from lead goblets, because it tasted better that way. What happened? Their grey cells decayed and the Empire fell, goblets tumbling down like nine-pins.'

'How do you know all this?'

'You see there was this patent application…' I started, but George held up his hand and stopped me.

'I am sure your patent application was absolutely fascinating, Alfie. But what was the other reason?'

'I would like to preserve your sketches and jottings as records of our discussions.'

'All right, but don't publish your notes without sharing the royalties with me,' said George, passing the napkin to me.

I must tell you something about George and me here. Both of us like to sketch and draw cartoons. So, I am going to include in my narration the drawings George made during our discussions. These technical drawings have been redrawn with the help of an artist friend to make them more presentable. I have also included some cartoons George and I have drawn for fun. I hope you will like them.

'Where were we before you rudely interrupted me?' George resumed our journey into the interior of the Sun. 'Yes, the nuclear reactions. To begin with we have these hydrogen atoms at the Sun's core stripped of their electrons. This we already discussed. At a temperature of millions of degrees in the stellar core, the hydrogen nuclei - or equivalently the protons - and the free electrons would be flying around at breakneck speeds, colliding incessantly. This enables them to interact with one another. Now the stage is set for nuclear transformations. Four hydrogen nuclei undergo a chain of reactions, combining to form the final product, namely a helium nucleus. A helium nucleus is made up of two protons and two neutrons. A neutron, as you know, is an elementary particle just like a proton. Except that it is neutral carrying no charge and it is a wee bit heavier than a proton.'

'Don't the protons carrying positive charge repel one another through electromagnetic force? How can they stick together?'

'Good question,' remarked George, and went on to give his explanation to my query. 'The answer is the nuclear forces. These forces are strongly attractive. And they overcome the electrical repulsion between protons and hold the helium nucleus together. Now here is the extraordinary fact that underlies this nuclear fusion or the thermonuclear reaction. When you add the individual masses of the four hydrogen nuclei we started with, the sum exceeds the mass of a helium nucleus, the final product, by a minute quantity. This mass difference is converted into energy in the form of heat and radiation during nuclear fusion. The conversion is in accordance with Einstein's famous formula $E=mc^2$, which says that energy released is equal to the mass difference times the square of the speed of light.'

'A formula, which even a child knows nowadays,' I said. 'But I am a bit confused here.'

'I thought I had made myself perfectly clear. Any way, go ahead, what is your confusion?'

'Protons are indivisible elementary particles with fixed masses, aren't they?'

'Absolutely.'

'So when they form helium, chips don't fly off or anything like that thereby losing mass, do they?'

'Of course not.'

'Then how come the mass of a helium nucleus is less than the sum of the individual masses of the four protons?' I asked. 'As a matter of fact, since neutrons are a bit heavier than protons, the combined mass of two protons and two neutrons should be more than that of four protons. In other words, the helium nucleus should be heavier than the four hydrogen nuclei put together. So, why is it the other way around?'

George inclined his head and regarded me with half closed eyes. 'You do like to ask these probing questions, don't you? Quite inconvenient, I must say.'

I knew that George was inwardly quite pleased. He enjoys putting across tricky ideas in a simplified form.

'This takes some explaining. You will have to be a bit patient.'

'That is no problem. I am patience personified.'

'First of all, we can speak of mass and energy interchangeably, since they are equivalent and inter-convertible as was shown by good old Einstein. We will talk about this equivalence in a little more detail later on. So, when we talk about mass, we must include energy as well. Or, in other words, we shall be speaking of the combined mass-energy. Secondly, total mass-energy is conserved, it can neither be created nor destroyed.'

'Agreed.'

'Now let us take the helium nucleus. As you pointed out, the total mass of the two protons and the two neutrons together exceeds the mass of the helium nucleus they make up. Therefore, we come to the strange conclusion that the helium nucleus must contain an amount of negative energy exactly equivalent to this mass difference. Equivalently, add this negative energy to the total mass of the constituents, namely two protons and two neutrons, and you get the mass of the helium nucleus. Simple arithmetic, which even you can do. This negative energy is known as the *binding energy*.'

'More and more confusion! How can energy be negative? All energy we observe and measure in nature is positive, I thought.'

'You are right. But energy too has its own credit and debit rules. Potential energy and energy in a bound system are not in a manifest form. They can be negative. You follow?'

'Not yet, but I am sure I shall, once you have completed your explanation.'

'Fair enough. Suppose you have to do work *on* a system to take it from one state to another. Then this work is stored as positive energy. For instance, take two like charges, say two protons. Far away from each other, their interaction is negligible. Now, in order to bring them near to each other, you have to do some work in overcoming their mutual repulsion. And this work becomes the positive potential energy of the two protons. They have to be held together by some other force. This can be an unstable situation. Under some external disturbance, the protons can fly apart carrying away the stored positive potential energy. This potential energy has now been converted into their kinetic energy.'

'I can think of a human analogy.'

'What is that?' George was curious to know.

'Suppose you have a couple who do not particularly like each other. And you are asked to arrange their marriage. A shotgun marriage so to speak. Then you have to put in considerable effort and do work to bring them together. The situation can be highly unstable. Some external influence, maybe a flickering flame from the past, could possibly send them flying apart.'

'Crazy analogy, but apt I must admit.'

'You have told me about positive energy. How about negative energy then?'

'All right. Now we must consider interactions that are attractive. Take, for example, the electrostatic force between two opposite charges or gravitation acting between two masses. To bring the two together you don't have to do any work at all. On the contrary, they themselves move towards each other under mutual attraction. And *they* do the work. Equivalently the work done *on* them by you is negative. Now we have a bound system with negative potential energy. Even if they are orbiting each other as in the case of an atom or planetary motion, one can show that the total energy – positive kinetic energy plus negative potential energy – is negative. Consequently, in order to take the two particles or objects apart and break up the system, you have to do work and supply positive energy.'

'The human analogy is now in the reverse,' I commented. 'Two people in love come close to each other and bond together naturally. No external influence needed. But it takes all your effort to separate them. What a pity though! Human attraction can weaken and wane, whereas physical forces in nature are permanent.'

'True enough. Now, when we deal with elementary particles and their interactions, we are in the realm of quantum theory, which is radically different from classical physics. Nevertheless, the underlying principle is the same. In the case of nuclear fusion, four protons are brought together through collisions at high temperature overcoming their mutual repulsion. Because of the ensuing nuclear reactions, we are left with two protons and two neutrons forming a helium nucleus. The nuclear interaction among them is extremely strong and moreover attractive. This leads to the negative binding energy of the nucleus, which is responsible for the lower mass of the helium nucleus as compared to its constituents, namely two protons and two neutrons. Furthermore, the mass of the helium nucleus turns out to be less than that of the four protons we started with as well. And, as we saw, this mass difference is released during nuclear fusion. Got it?'

'Ah, I think I understand the energetics of nuclear fusion now,' I said. 'How about nuclear fission?'

'Well, the energy principle works in the case of nuclear fission also. You initially have a heavy nucleus with some binding energy. By fission, you can split the nucleus into fragments – elements lighter than the original one – whose internal binding is stronger. This makes for a more stable configuration.'

'Like having a large commune to begin with, but finding that it would be a happier and healthier situation to break it up into smaller families.'

'Alfie, your analogies are getting crazier and crazier!' exclaimed George.

'That is because the physics is becoming stranger and stranger,' I countered.

'I think you are right,' admitted George and continued. 'Coming back to nuclear fission, a slow neutron can break up a uranium nucleus into barium and krypton – almost equal fragments – releasing nuclear energy. Three more neutrons are ejected in this process leading to a chain reaction splitting more and more nuclei. This process is used in nuclear reactors for energy production.'

'Or in making a nuclear bomb.'

'That is right, unfortunately. Whew, that was quite a bit of explanation, don't you agree? I must wet my whistle.'

After a pause George continued. 'Let us get back to the interior of the Sun. The energy generated in a single thermonuclear reaction, when four hydrogen atoms combine to form a helium atom, is minute. But the Sun is huge, containing an enormous amount of hydrogen. Each second at the Sun's core 564 million tons of hydrogen are converted into 560 million tons of helium.'

'Which means every second 4 million tons of mass are transformed into energy. And you have to multiply this by the square of the speed of light to get the actual amount of energy released. How much would that be, George?'

George took out a small piece of paper from one of his pockets. Scrawled on them were some numbers. 'I have jotted down some figures that should interest you. You will probably file them away somewhere in your head. You know what a watt is?'

'Come on, George, every one who pays electricity bills knows that. It is the unit of power, the energy generated or consumed per second, named after James Watt, the inventor of the steam engine. Maybe a tautology, but a hundred-watt light bulb obviously uses up a power of hundred watts.'

'Good. Each second, the Sun generates some 400 trillion-trillion watts of power. Remember a trillion is one followed by 12 zeroes, so the energy released within the solar core measured in watts is 4 followed by 26 zeroes. Now the total amount of electrical power being used in the whole world is about 10 trillion watts. In other words, the energy the sun produces in one second is equivalent to what mankind would use in 40 trillion seconds or in a million years!'

'What a monstrous irony!'

'How do you mean?'

'The same thermonuclear energy, that keeps the sun shining, causes the explosion of a hydrogen bomb, doesn't it?'

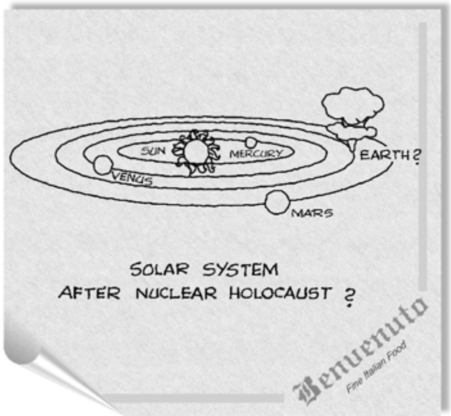
'Again, unfortunately, yes,' answered George.

'I remember that if one ton of TNT explodes in a second, it yields a power of 4 billion watts.'

'That means that in one second the sun produces an energy equivalent of 100 billion megatons of TNT.'

'Those numbers make your head swim, don't they? All that energy in terms of tons of TNT is confined to the sun. But look at what is happening right here on the earth. The most powerful hydrogen bomb is equivalent to about 60 megatons of TNT. And the stockpiled nuclear arsenal amounts to some ten thousand megatons of TNT. For every human being there is more than a ton of TNT in store. Enough to wipe out the entire human race many times over!'

George had been sketching while we were having this conversation. He showed me what he had drawn. It was a schematic diagram of the Solar System. 'This is how the Solar System would look like if there were ever to be a nuclear holocaust, Alfie,' sighed George. The drawing showed an enormous mushroom cloud orbiting the sun where the earth should have been. It gave me a sick feeling.



'Sorry, Alfie. Let us get back to the Sun, which is a more cheerful subject,' George said and continued. 'So in the Sun's core the hydrogen keeps burning. This is not really ordinary burning, as we know. But that is the way the heat production through nuclear reactions is colloquially described. The nuclear furnace at the heart of the Sun keeps going for ten billion years. Of which five billion years are already gone. Sun shines on. But then the situation takes a dramatic turn. It is a somewhat complex story from now on. Let me give you a brief, simplified account of the events that follow. I shall concentrate more on the Sun.'

'Ah, our own nearest and dearest star!'

'Let me warn you. I am leaving out many details and may not follow the exact order of changes that occur within the Sun.'

'Whatever you say, boss,' I agreed.

Bruno served us dessert, Biscuit Tortoni with a creamy hazelnut sauce, and withdrew. George took a bite and continued.

'Now, in ten billion years most of the hydrogen at the Sun's core would be converted into helium. There is no longer enough heat production to balance the gravity of the core's mass. So what happens? The core shrinks under its own weight and gets heated up. And this heat is conveyed to the shell surrounding the core. The shell is of course made up of hydrogen, which starts burning. The outer part of the Sun in turn gets heated and bloats up. And as you know, an expanding gas cools down. So, the surface temperature drops because of this expansion. The Sun, grown gigantic by now, glows red. The Sun has turned into a red giant.'

'How big is gigantic?' I wanted to know.

'The Sun in its reincarnation as a red giant is some two hundred times its normal size, in terms of its radius that is. Big enough all right.'

'What happens to the planets then?'

'Mercury and Venus will be swallowed up by the immense blob of fire that the Sun has become.'

'Poor things! And what about our dear Earth?'

'The Earth is destined for hardly a better fate. If it is not gobbled up, it will still be scorched to a cinder. Nothing living survives the heat. The Earth is now a dead planet enveloped by thick clouds rising from the boiling oceans.'

'What is going on with the Sun's core in the meantime?'

'The nuclear reactions within the Sun's core have come to a halt. But the hydrogen in the outer envelope keeps burning. And the region where this happens keeps growing outwards. Helium, the ash of the hydrogen burning, so to speak, goes on getting deposited on the core. Now, the core is under tremendous gravitational compression. As a result, it heats up enormously from 15 million degrees to some 100 million degrees.'

'That is unimaginably hot, George,' I remarked.

'Indeed. At this temperature even helium is ignited. As a result, carbon and oxygen are produced through nuclear reactions.'

'How long does this process take?'

'Oh, in a star like our Sun this helium flash, as it is called, lasts just a few seconds. In heavier stars it can be prolonged. Well, coming back to the Sun, hydrogen burning in the envelope continues and the star becomes a red supergiant reaching out to the planet Mars.'

'All this seems to me like a lot of turmoil. And it looks like the star is trying to prolong its own life.'

'What else do you expect, Alfie? That is what happens with the onset of old age and the approach of death. During the death throes of a star like our Sun, it sheds its outer layers, which expand away in glowing colours.'

'Again my question, what has happened to the inner core in the meanwhile?'

'The core has contracted to the size of the Earth, that is about a hundred times smaller than its original radius or a million times smaller in volume.'

'That means it has become awfully dense.'

'Absolutely. The density is now around a million grams per cubic centimetre. Or tens of tons per cubic inch. Do you have any idea how dense that is? A chunk of matter the size of a sugar cube, if brought to the earth, would be as heavy as an elephant.'

'Amazing! So this is a totally new phase for the Sun?'

'Exactly. The sun has become a white dwarf. White because the surface shines bright as it has been heated up when the core contracts. But it slowly cools down and shines no more. We can call it a black dwarf. The sun has entered its eternal resting place now. The letter D in BED, which stands for the death of the star, has been reached.'

'Let me get something clear. There is no longer any heat production within the sun's core or within the white dwarf. Isn't that true?'

'Correct. All nuclear processes have come to an end.'

'Then how does the white dwarf hold up against its own gravity?'

'A wonderfully perceptive question, Alfie!' George observed appreciatively. 'This takes some explaining. Here we enter the world of quantum physics, just as in the case of the nuclear reactions occurring in the solar interior. And quantum physics is a strange world full of surprises, you know. As we have already seen, the matter in the white dwarf is in a highly compressed state. The electrons are no longer held by individual nuclei, but move freely and behave like a gas – an electron gas as it is known. Not an ordinary gas though, because of the strange quantum effects. As a result, the electron gas exerts a novel kind of pressure. This is radically different from the pressure due to the thermal motion of the particles in a hot gas. The new kind of pressure is independent of the temperature of the electrons. It acts even if the temperature is absolute zero. As a matter of fact, in the absence of heat generation, the electron gas may be considered to be at absolute zero temperature for all practical purposes.'

I waited patiently as George paused for a moment.

'Now, Alfie, at high temperatures, a gas acts as a classical system having a continuous distribution of energies,' continued George. 'This is not so in the case of a quantum system such as, for instance, the hydrogen atom. You have now discrete energy levels. They are labelled by integers, quantum numbers as they are called, from zero upwards, corresponding to increasing values of the energy. This is true of the electron gas also. Is that clear?'

'Yes, indeed,' I replied.

'Good. Take the constituents of the atom, namely the electrons, the protons, and the neutrons. They are elementary particles with spin.'

'You mean they are like tiny spinning tops?'

'Well, Alfie, such a visualization is confined to classical physics,' clarified George. 'In quantum theory you just assign quantum numbers to describe physical quantities like energy, angular momentum and so on. The elementary particles we just mentioned are assigned half as their spin quantum number. Furthermore, half and minus half correspond to spins in opposite directions, or spin up and spin down, as the nomenclature goes. Are you with me?'

George wanted to be sure that I was following him closely in the unfamiliar realm of the quantum.

'One question, George,' I put in. 'Are there particles with spin quantum numbers other than half?'

'Oh, yes: The photon has spin one and there are other elementary particles that have zero spin,' replied George. 'Now, here comes a rather unusual quantum effect known as the exclusion principle. The brilliant Austrian physicist, Wolfgang Pauli, formulated it. Particles with spin half obey this principle, which essentially stipulates in the present case that any given energy level may be occupied by only two electrons, and that they must also have opposite spins. The electrons in the interior of a white dwarf start occupying the discrete energy levels, from the lowest values to higher ones. Once two electrons have occupied an energy level, others will have to go to higher levels. This also places a limitation on the location of the electrons. Two electrons in the same state can come close enough. But, any other electron trying to come near is repelled. This phenomenon caused by the Pauli exclusion principle manifests itself as a new kind of pressure, which can counteract gravity. And, mind you, this is a purely quantum mechanical effect.'

'This calls for an analogy!' I said rubbing my palms together with glee.

'All right, let us have it,' said George patiently.

'Let us say two electrons of opposite spins are like two members of opposite sexes. Now take a bus, for example, where there are rows of two adjacent seats. Suppose the quantum bus company has made the rule that these seats have to be occupied only by two people of opposite sex.'

'Married I suppose.'

'Not necessarily. You said the electrons are free, remember? Also tickets are numbered and the couples have to occupy seats with successively increasing numbers. Once a pair of seats is occupied, a third person has to leave the couple alone and take another seat. So this unwanted stranger is repelled away.'

'I should remember your analogies, Alfie. Who knows? They may come in handy after all when I teach physics to non-science majors, *Physics for Poets* as the course is called,' said George. 'To sum up, the exclusion principle gives rise to a new kind of pressure in the case of the electron gas in the white dwarf. It is purely a quantum effect. This pressure is known as the degeneracy pressure.'

'Why *degenerate*? Sounds perverse to me.'

'I protest. There is nothing perverse about electrons,' remarked George. 'Degeneracy is a technical term. Under normal conditions of the star at high temperatures, the electrons can have all sorts of energies. When there is no longer any heating by nuclear reactions, as in the case of the white dwarf, one can consider the energy distribution to have degenerated into the ordered discrete levels, we talked about just now, with only two electrons in each level. That is how the term degeneracy arises. Oh, forget all these technicalities, Alfie. What is important to us is that the degenerate electron gas in the white dwarf counteracts its gravity.'

'A degenerate dwarf! How grotesque. I can see the sensational headlines splashed across the Hollywood tabloids. A shining star turns into a degenerate dwarf!' I commented. 'All right, I now know something about white dwarfs. But what about black holes, George? They are obviously not white.'

'Patience, my boy, patience,' advised George. 'There are still a couple of steps to go before we can think of black holes. We know that a star like our Sun becomes a white dwarf at the end of its evolution. Once it was believed that this fate awaited all stars. This was not to be. A star of mass more than about one and a half times that of the Sun would not end up as a white dwarf at all. This upper limit to the mass of white dwarfs is known as the Chandrasekhar limit, named after its celebrated discoverer.'

'You mean a star heavier than the Sun behaves quite differently?'

'Exactly. Both during its life and in its death. Because of the higher mass, the gravitational pull towards the centre is much more than in a lighter star. So in the core, higher temperatures are generated and more power is released. Correspondingly, the gas pressure in the interior of the heavy star is also greater. And the stronger gravitational force is effectively counteracted by this enhanced gas pressure.'

'You told me that the Sun's life span is about 10 billion years. Now, if the heavier star has more mass to burn, it should live longer than our Sun. Am I right?

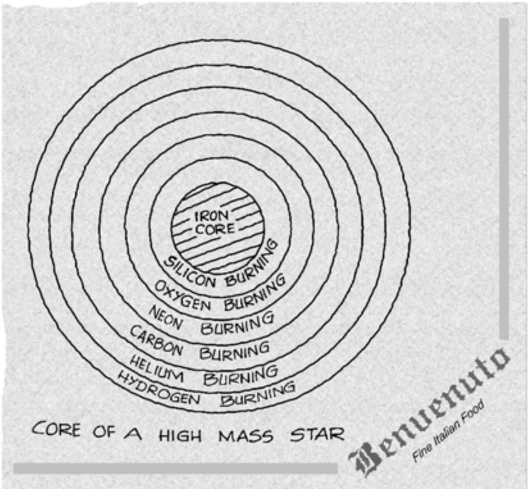
'Sorry, Alfie. You are wrong for once. Let me explain why. Because of the tremendous temperatures within the heavy stars, energy generation takes place at enormous rates. Consequently, these fat cats burn themselves up pretty fast, even though they have a lot of mass to begin with.'

'No different from some humans!'

'You seem to be so eager to connect stellar evolution to human affairs, Alfie,' observed George. 'All right then. Let us compare the life of the Sun with that of a heavier star. Scale down our Sun's life span to one year. On this time scale, a star seven times more massive than the Sun lasts for about a day. And, one that has eighteen solar masses survives for just nine hours.'

'Well, well, well, what do you know! Let me take another guess, which I think is correct. The high temperatures at the stellar cores of these massive stars must alter the nuclear reactions that go on inside too. Say I am right!'

'I'll say you are right!' confirmed George with a smile. 'Once again, let me give you just the gist of what happens within a massive star. As a result of the high temperatures, nuclear burning does not stop at helium produced from hydrogen. Helium, the ash of hydrogen burning, is further converted into carbon. This way, a whole sequence of elements is cooked up within the interiors of heavy stars. Neon, oxygen, silicon, and so forth, finally ending up with iron. Then there can be no more nuclear reactions, since we have hit the most stable configuration. What do we have as the end result of all this? An onion-like structure with an iron core surrounded by shells of the ashes left behind by the successive thermonuclear transformations.'



'I suppose once again the core is condensed even more than the white dwarf. If so, I repeat the question I asked in the case of a white dwarf. What counteracts gravity?'

'Similar questions have similar answers, my boy,' George proceeded to answer my question. 'Since the nuclear reactions have stopped, there is no longer any heat generation, no gas pressure to balance gravity. Just as happened in the case of the white dwarf. It is quite ironical, you know.'

'What is ironical?' I asked.

'Gravity's role in all this,' answered George. 'Gravity gave birth to the star and regulated its life, didn't it? But now it has turned into a devastating force. Iron nuclei are crushed and broken up by the gravitational compression. And the electrons are pushed back into the nuclei turning all protons into neutrons. The stellar core is now composed of just neutrons, a vast sea of neutrons, or neutron gas. This neutron gas now behaves exactly like the electron gas within the white dwarf.'

'We are back to quantum effects then?'

'Indeed. Neutrons, like electrons, are particles with spin that obey Pauli's exclusion principle. As a result, the degeneracy pressure of the neutron gas counteracts gravity. We have now a neutron star made up of neutrons packed like billiard balls.'

'The white dwarf is the size of the Earth you said. How big is a neutron star, George?'

'You mean how small, Alfie. Its radius is typically around a mere ten kilometres. You could cover the distance from the centre to the surface easily, except that you would be crushed out of existence by the compression of the matter.'

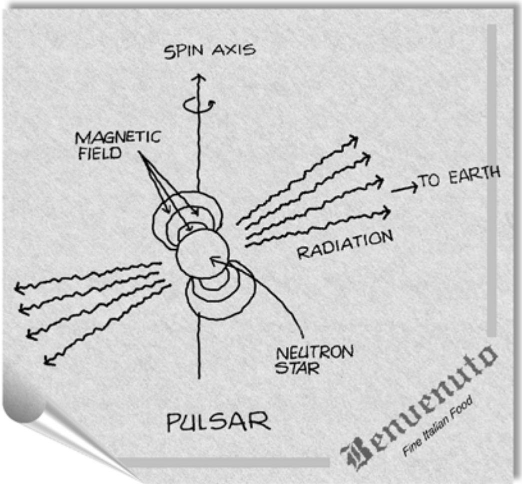
'That means matter of the order of a solar mass, packed into a sphere of ten kilometre's radius! The density must be terribly high.'

'You bet. Because the star is now made up of closely packed neutrons, it is of nuclear density, which is phenomenal. About one hundred trillion grams per cubic centimetre. Can you imagine that! A spoonful of neutron-star matter if brought to the Earth would weigh as much as all human beings put together. Present population, of course.'

Even with this illustrative analogy, it was impossible to imagine such high densities. Well, that is how astrophysics works, I thought, and continued my enquiry.

'George, you told me that a white dwarf shines merely because of the heat it has retained from its shrinking. When it cools completely and becomes a black dwarf, it no longer shines and becomes invisible. How about a neutron star? Does it shine? Is there any way one can detect a neutron star observationally?'

'Well, Alfie, the scenario we have now is rather different from the one we had in the case of the white dwarf,' George went on to explain. 'When the core collapses giving birth to the neutron star, the surface of this monstrously heavy new-born baby is at a temperature of about a million degrees. At such temperatures, the surface would emit X-rays. Of course, the neutron star will cool off eventually and cease to glow. Obviously the neutron star would be invisible in this state. Nevertheless, there is something very interesting that can happen. Neutron stars are often endowed with a pair of beacons of radiation, radiation composed of different wavelengths. This could possibly include visible light too. As the star spins, we would observe a flash of radiation each time we come in the line of the radiation beam. Very much as in the case of a lighthouse. So the neutron star keeps sending pulses of radiation at constant intervals. Such neutron stars are called *pulsars*. Neutron stars spin so steadily, that the pulses sent out by pulsars are extraordinarily regular. The regularity of the pulses is comparable to the accuracy of atomic clocks. Because of this, when the pulsars were first detected, astronomers wondered whether some extra terrestrial beings might be sending these signals. So half jokingly, the new objects were christened LGM or Little Green Men.'



'That is quaint. Still, a question remains. You said there is no energy generation going on inside the neutron star.'

'That's right.'

'Then how are these beams of radiation produced?'

'That is a million-dollar question, Alfie. Neutron stars happen to come with very strong magnetic fields attached to them. Charged particles moving in these magnetic fields are supposed to produce the beams of radiation. Nobody knows the exact details of such a mechanism. I would be rich and famous, if I found out the answer. I wouldn't be sitting here giving away my hard-earned knowledge, you know.'

'All right, let us say we are in a state of blissful ignorance here,' I said. 'To sum up what you have told me then, stars lighter than the Chandrasekhar limit end up as white dwarfs. And all those that are heavier rest in peace as neutron stars.'

'Not so fast, Alfie,' cautioned George. 'Even neutron stars, like white dwarfs, have a mass limit. This was demonstrated by Robert Oppenheimer and his coworkers in the thirties.'

'*Oppie, Was there any divinity in your Trinity?*' I crooned.

'What was that?' George sat up in surprise. 'Is that something about Oppenheimer? His friends called him Oppie, you know.'

'Oh, well, you don't listen to modern songs, as I do,' I said. 'I just quoted a line from the song entitled *In the Darkness of the Rising Sun,* by a group called *Nam's Nanosingers*. It is about the atomic bomb and is addressed to Oppenheimer.'

'Do you remember the full song, Alfie?' asked George. 'I would like to hear it.'

'Sure, George. Here is the song in its entirety,' I recited the song for George.

Oppie, Was there any divinity in your Trinity?
A bit of Uranium and a dash of Plutonium
Made up your lethal Oppium.
When the trial became real
And the spark from hell earthward fell,
Did your Trinity cry to see thousands die
In the darkness of the rising sun?
When mothers wept as children forever slept
In the darkness of the rising sun?
Will the future generation be free from nuclear veneration?
Will a candle be lit where the atom split
In the darkness of the rising sun?
In the blinding darkness of the rising sun?

'The test site was code-named *Trinity*,' I went on after reciting the song. 'Even the Committee that conducted the proceedings against Oppenheimer in regard to his security clearance was surprised to hear that. The words *rising sun* in the song allude both to Japan, the Land of the Rising Sun, and to how Oppenheimer described his impression of the explosion. Oppenheimer said that, when he saw the ball of fire, two passages in the *Bhagavad Gita*, the sacred Hindu text, came to his mind. One was:

The radiance of a thousand suns
which suddenly illuminate the heavens
all in one moment – thus
the splendour of the Lord.

And the other:

And I am Death, who taketh all,
Who shatters worlds…

George, even to a person who is not religious, this mixing up of the sacred with a weapon of mass destruction would appear to be totally incongruous, to say the least.'

George sighed deeply. 'I know, Alfie. It is a sad chapter in human history. God knows when and how it will all end.'

George fell silent. After collecting his thoughts, he resumed the discussion. 'Yes, Oppenheimer has come to be known as the father of the atomic bomb. But astrophysicists will hopefully remember him for his pioneering work on the neutron-star mass limit and gravitational collapse. A lot has been done in this field since Oppenheimer's time, as our knowledge of nuclear interactions has steadily increased. But even then, that knowledge is not really complete, especially at the phenomenal compressions that exist in the core of a neutron star. In any case, the latest value for the neutron-star mass limit falls between about one-and-a-half to three-and-a-half solar masses. However, the neutron-star mass limit has been shown theoretically to be roughly four times the solar mass, assuming the conditions within the core of the star to have reached some extreme allowable limit. So if you want to be absolutely certain of this limit, you could take it as, say, five solar masses.'

'How about observational values for the neutron stars?'

'Good question. It so happens that the neutron stars, or pulsars, that have been observed so far have masses of about the Chandrasekhar limit. So, some people think if an invisible star has a mass of two solar masses or more, then it has crossed the neutron-star mass limit. But we can take a conservative theoretical limit of, say, five solar masses as our limit. After all, Alfie, we have to be absolutely certain of the identity in a line-up.'

'All right, what happens to stellar cores that exceed this limit?'

'Aha, we are now getting to the most interesting part of our story, Alfie,' George said with relish. 'There is no known force that can withstand the intense gravity within such a heavy core. Gravitational collapse is now inevitable. The collapse is catastrophic, continuous and relentless. And, Alfie, what is the final result? It is the formation of a black hole! The bizarre end product of a super-massive star that has exhausted its nuclear fuel. The long awaited grand finale to the symphony of stellar evolution.'

At last, we had arrived at the black hole. Evidently it was just the beginning.

'Again, what fate awaits all that matter that collapsed?' I asked the obvious question.

'Ah, there lies one of the greatest mysteries in physics,' commented George. 'Nobody knows the answer, Alfie. Let us not jump into this unknown realm right now. It will take us a few sessions before we come to that ultimate question. First we must understand the nature of black holes and their properties. To do that, we need Einstein's general theory of relativity. For a starter, we must go back to the very origins of gravitational theory. To the great Isaac Newton himself and his universal law of gravitation. Its origin, its workings, and its limitations. Only then can we appreciate the true nature of a black hole. This journey, my dear Alfie, we shall begin in our next session.'

What I had heard so far was incredibly astounding to say the least. The blazing life of a star, lasting billions of years, finally culminating in inevitable stellar death leading to three different kinds of final states: White Dwarfs, Neutron Stars, and Black Holes. Strange, but in a way simple as well.

'All this stellar evolution stuff sounds like the theme of an exciting novel,' I observed.

'Well, when described in simple language it does sound like a story, Alfie,' remarked George. 'But don't forget, beneath it all, there are deep concepts, hard theory and complicated mathematical computations.'

'I don't doubt that, George,' I said. 'But you know what Ernest Rutherford, who was not all that big on mathematics, told Niels Bohr?'

'No, what did he say?'

'Rutherford said that a good theoretician should be able to explain his theory to a barmaid.'

George clapped his hands with glee and called out to Bruno, who was passing by. 'Bruno, did you hear what Alfie just said? We want to explain our theories to barmaids. Why don't you hire some?'

Bruno came over and looked George straight in the eyes. 'I don't know what you two have been talking about. But I heard things like shamelessly naked, attraction between unmarried couples, how to seat them in a bus and who knows what else. Now you want me to hire barmaids so you can tell them all this? *Impossibile! Mai!* Never!' Trying unsuccessfully to suppress his mirth, Bruno strode away hurriedly.

George laughed and said, 'Alfie, we have covered quite a bit of ground today. Before we wind up, let me tell you a little about stellar explosions. For instance, after a white dwarf is formed, it sometimes flares up. Often, this is due to matter being dumped on it by its companion, when the dwarf is paired off with another normal star. The two stars form a binary system. Take for example, Sirius, the brightest star in the sky. It is actually a binary star system. The bright star has a faint companion, which is a white dwarf. The two stars go around each other. Now, a flare of a white dwarf is called a *nova* by modern astronomers. A word borrowed from antiquity, which means 'new' in Latin. Whenever a star that is not visible to the naked eye brightens, it appears as though a new star has appeared in the sky. Once upon a time, such an event was called a *nova* in general, although this term now refers to moderately strong outbursts of certain stars. On the other hand, for instance, the Chinese astronomer Yang Wei-Te saw a spectacular event in the sky in 1054 AD. A new star, or 'guest star', had suddenly appeared that was visible in broad daylight for more than three weeks before it faded away. This was in the constellation Taurus, the Bull. Now we know that it was not a *nova* in the technical terminology of the present day. It was a *supernova*.'

'A supernova! That is a familiar word even to a layman nowadays. An immense stellar explosion!'

'For a layman you are always singularly well informed, Alfie,' commended George. 'Yes, a supernova is a spectacular stellar explosion. As we saw, a neutron star, not a white dwarf, is formed by the catastrophic gravitational collapse of a heavy stellar core. Then the outer envelope of the star explodes violently. The energy released is enormous, some hundred million times the luminosity of the Sun. The exploded star shines as bright as the stars of an entire galaxy put together. This is what we call a supernova. Remember elements up to iron are created within a star? Now heavier elements are formed in the brief, intense heat generated in a supernova. But that is not the end. New stars can be formed out of the debris of a supernova, which now contains all the elements that exist. As a matter of fact, our Sun is made up of such recycled stellar matter and so are the planets. That is how our Earth happens to contain all the elements needed for life. Therefore, Alfie, you and I are parts of the same star that exploded way back in the past. Think about it!'

Bruno placed before us two small cut glasses filled with honey-coloured liqueur and said, 'Amoretto. Almond flavour goes well with hazelnut sauce served with dessert.'

'Thanks, Bruno,' George said and went on. 'The supernova that was observed in 1054 left behind a remnant made up of glowing gases. This remnant looks like a crab and is called the Crab Nebula.'

'I have seen a photograph of the Crab Nebula. A network of glowing multicoloured filaments enveloping a diffuse cloud of gas. It is beautiful.'

'Many celestial objects are breathtakingly beautiful, Alfie! The Crab Nebula contains a pulsar, the Crab Pulsar, which is the relic of the star that exploded.'

'How far is the Crab Nebula, George?' I asked.

'It is about six thousand and five hundred light years from us, Alfie,' answered George. 'That means the light from the exploded star travelled for that many years before the supernova was sighted in 1054 AD. In other words, the star exploded around five thousand and five hundred BC.'

'Aha, surely that is a case of predestination, George,' I commented. 'The star exploded just at the right moment so that Yang Wei-Te might see the supernova!'

'You have the weirdest imagination, Alfie,' George shook his head. 'Well, there are a handful of historical supernovae like the one that was sighted in 1054. Some of them were observed and recorded in the past by astronomers all over the world – by the Arabs, Indians, Chinese, Japanese, Koreans, and so on,' George continued. 'Let me mention a couple of them. The great observational astronomer Tycho Brahe sighted one of them in the constellation Cassiopeia in 1572. As I told you, in those days a star that suddenly flared up was called a *nova*, a new star. The explosion did not leave behind a neutron star but only diffuse gas that has been identified at both radio and optical wavelengths. In the same constellation Cassiopeia, there is another well-known supernova remnant. It is a shell of gas, a strong source of X-rays and radio waves. This supernova remnant is called Cas A, 'Cas' being the abbreviation for Cassiopeia. No one seems to have observed the *nova* associated with Cas A. In 1604, Kepler also observed a supernova in the constellation Ophiuchus. No neutron star resulted from this stellar explosion either. Both of these celestial events, or *novae*, were noticed by Galileo as well. Since then no supernova has been observed. There is a saying that a supernova is seen in our galaxy only when there is a great astronomer around. The implication is obvious.' George added in a stage whisper, 'Alfie, never mention this to the astronomers though. They get very upset.'

'But, George, I read quite often in the newspapers about some supernova or the other being detected. What about them?' I asked.

'Ah, several supernovae are observed each year in other galaxies, not our own Milky Way. Since Kepler's time no new supernova has been observed in our galaxy.'

George lapsed into silence. Eyes closed, he seemed to be in deep contemplation. He opened his eyes slowly and turned to me.

'You know, Alfie, when you study the stars, you feel as if transported to a totally different plane. To another world that enshrines everything that is beautiful and noble. There is music even in the names of the stars and the constellations. Whether it is Greek like *Alcyone*, *Antares*, *Kornephoros*, and *Procyon;* Latin like *Proxima Centauri*, *Corona Borealis*, and *Coma Berenices;* or Arab like *Aldebaran*, *Alnilam*, *Ras al Hawwa*, and *Al Ahir al Nahar*. Look at the vibrant colours of the stars, the nebulae, and the galaxies. They are like the brush strokes of a master artist, aren't they? They seem to have been made for the very purpose of painting the myths and legends of Mankind as they do. Most of all, we have learnt so much about the stars that are so far away. Just sitting here on our little planet Earth! Isn't that a marvel? How can I describe the way I feel when I look at the stars, Alfie? The night sky is like the façade of a great cathedral or a temple. There are wonderful treasures hidden behind it waiting to be discovered. But we may never reach the innermost sanctum. Hopefully, never ever!'

George shook his head and placed his hands firmly on the table as if feeling the reality of his earthly surroundings. 'Well, Alfie, I must go home. After all the wonderful food, drink and talk, I couldn't possibly go back to work. Thanks, Alfie.'

'Thanks for what?' I asked in surprise.

'Thanks for listening. It feels so good to tell what little you know to someone who appreciates. Bruno, I can't thank you enough for your superb food.'

Bruno smiled and replied, 'I just heard you thanking our friend here for listening. Same way maybe I must thank you for enjoying my food.'

'All right, Bruno, you win. Alfie, I almost forgot. Here is a short book on astronomy. Quite nice. Tells you how to locate the constellations and the stories related to them. Also, it explains some astrophysics of the stars. I am sure you will enjoy reading it. Take care, Alfie.'

George left. I kept thinking about all that I had heard. About the stars, night's candles that were lit by accident, that burn for aeons, to be inevitably extinguished in the end. The music playing in the background was majestic. I recognised it. It was the Overture from Mozart's *Don Giovanni*. Lost in my own thoughts, listening to the solemn strains of that magnificent music, I lingered on for a while before going home.

Chapter 3

THE CASANOVA CONNECTION

The night was crisp and clear. I went up to the terrace, taking with me a pair of binoculars, the book of astronomy George had given me, and a flashlight to read it by. Despite the city lights, I could see countless stars sparkling against the black velvet of the night sky. Some bright ones shone in solitary splendour, while others huddled together in the cold. Here and there, faint ones were sprinkled in patches of luminous dust. I could make out the Milky Way as well, a mysterious glow stretched across from horizon to horizon. *What would be the joy of a star but for those who behold it*, wrote Nietzsche. I felt elated to imagine that all those stars were shining just for me and that I was giving them joy in return.

With the help of the little book, I could identify many of the stars and the major constellations. There was Polaris, the pole star, to begin with, fixed in the firmament around which the other stars marched in circles, some of the constellations turning upside down in the course of the night. I could easily see my old friend Orion, the one constellation I could recognise anytime. With the help of my binoculars, I could make out the Orion Nebula beneath the belt of the celestial hunter. It was just a smudge of light almost imperceptible to the unaided eye. Even the pair of binoculars did not reveal the brilliant, multicoloured spectacle of the nebula I had seen in books. Of course, those were photographs taken through powerful telescopes using sophisticated techniques. I memorized the patterns of a few other constellations in order to be able to identify them in the future.

I came down from the terrace in a state of euphoria having bathed in the starlight. And I was ready for a soothing soak in my beautiful bathtub. Submerged in the warm water, I read from the little book of astronomy the stories about the constellations I had seen from my rooftop. Soon, the bubbles produced by the special mixture that I had added to the bath water surrounded me on all sides. I was reminded of the *beaded bubbles winking at the brim* as

Keats had described those that sparkled in his glass of wine. The bubbles were gently pressing against me. They seemed to be trying to lift me upwards. I put the book aside, closed my eyes, and surrendered myself to the floating sensation that the buoyancy of the bubbles had created.

When I opened my eyes, I was indeed floating in dark outer space. Way below, I could see the Earth, couched in its sheath of clouds, glowing like a pearl. All around me shone millions of stars. They did not twinkle, as I was now way above the Earth's atmosphere. I could also make out the different colours of those stars – tinges of red, orange, yellow and blue.

As if materialising from empty space, an ethereal figure appeared in front of me, first the outline and then the inner form. It was a middle-aged man elegantly dressed in the fashion of the eighteenth century. His attire, including his powdered wig, was harmoniously coordinated in shades of grey and black. His cheeks were hollow and his lips pressed together into a mildly sardonic smile. As he gazed steadily at me with his translucent grey eyes, he seemed to be reading my innermost thoughts.

'Allow me to introduce myself, *signore*,' said this strange figure with a deep, formal bow. 'I am Giovanni Jacopo Casanova, your servant.'

What an incredible surprise, to meet the famous Casanova, of all people, here in outer space. I realised that, at the same time as he appeared, some beautiful music had also started playing in the background, which seemed strangely familiar. I could not recall where I had heard it, nor could I identify it. Casanova's smile widened a little as he spoke.

'Ah, that is from *Don Giovanni* by Mozart. Giovanni, the same name as mine and the same reputation. Mozart took lessons from me you know. But the poor boy proved to be a hopeless failure.'

What, I thought with surprise; Mozart had taken music lessons from Casanova! I never knew that.

'Contrary to what you may be thinking, *signore*, I am not a lowly music teacher,' remonstrated Casanova, drawing himself up with dignity. 'Amadeus took lessons from me in the fine art of winning over a lady, which unfortunately crass ignorance dubs seduction. He wanted to play the role of Don Giovanni in real life, for the sake of achieving authenticity, before embarking upon writing his opera. He should have confined himself to the less demanding rigors of music.'

Yes, I remembered having read somewhere that among the voluminous manuscripts left behind by Casanova, there were a couple of versions of a scene from *Don Giovanni*, written when Casanova and Mozart were together in Prague. I recalled too vague accounts of Mozart's attempts to follow in the footsteps of Don Giovanni under Casanova's tutelage. All this was interesting. But I could not figure out why Casanova had appeared amidst the stars.

'Ah, the *signore* is wondering why the great Casanova has appeared in the vast *vacuo* of the celestial realm,' Casanova read my thoughts and proceeded to clear up the mystery. 'For a most peculiar reason, *signore*, most peculiar! You have learnt, I presume, that in the constellation Cassiopeia, there exists the remnant of a stellar explosion in the form of a gas cloud. This said remnant is designated, in the unimaginative modern terms, as Cas A, whereas the brightening of the exploded star had once been aptly described as a *nova* or a new star. *Cas A* and *nova*, put together, happen to spell *Casanova*, my illustrious name. Fate, with its perverse sense of humour, therefore, conferred upon me the dubious honour of guiding the *signore* through some of the constellations.' He swept his hand to indicate the constellations that were visible. As he did so, against the backdrop of the constellations, the respective mythological figures took shape.

'Let me tell you in brief the Greek myths behind some of these constellations,' continued Casanova. 'We might as well begin with Heracles as the Greeks called him, better known as Hercules, the name given to him by the Romans.'

Domineering over the constellation named after him, the mighty Hercules stood in a heroic pose with one foot firmly planted on the head of the dragon he had subdued, the splendid constellation Draco.

'I am sure the *signore* knows all about Hercules, perhaps the most famous figure in Greek mythology, even if not the most prominent constellation in the night sky,' remarked Casanova. 'Hercules was born to a mortal woman, the Theban Princess Alcmene, and was sired by none other than Zeus, King of Gods. Zeus was notorious for going around the countryside in many different disguises producing offspring from earthly beauties. When gods themselves indulge in such diversions, *signore*, why blame poor mortals for following their example! Be that as it may, Hercules grew into a great hero possessed with enormous strength. He was destined to perform extraordinary feats in the course of carrying out his twelve labours, such as killing the awesome Nemean lion, eliminating the dreaded Hydra, the enormous and hideous water serpent with many heads, and so on and so forth. An entire book could be written about Hercules, but you would agree that we have no time even to read, let alone write, books.'

Close to Hercules, I could see another powerful man holding an enormous serpent in his arms. The serpent hissed as it twisted and turned while its long tail flapped around.

'That is Ophiuchus, a name compounded of two Greek words meaning serpent and to hold,' explained Casanova. 'This was the sobriquet given to the god Aesculapius, expert in the arts of medicine and unchallenged authority on the healing powers of plants and herbs. He is considered to be the first doctor of medicine, who, one can be sure, did not recourse to the abominable practices of my day such as bleeding the patients either literally or financially, or both. Ophiuchus, it is said, learnt all his skills from the serpent. One can only fritter away one's precious time in fruitless speculation as to how and where the serpent came to acquire its medicinal arcana, so we shall prudently desist from doing so.'

An expression of deep admiration lit up Casanova's face as he gazed away from the two men he had been describing. I turned in that direction to discover a most beautiful woman seated on a throne, dressed in regal attire and wearing a bejewelled crown.

'Ah, the *signore* has noticed the Queen, Cassiopeia, the celestial beauty' exulted Casanova. 'Alas, beauty begets vanity, and vanity inherits a loquacious tongue. Her boast that she was the most beautiful woman in the entire cosmos brought untold miseries upon Cassiopeia. It is a long tortuous story, involving her husband King Cepheus, their lovely daughter Andromeda, the valorous Prince Perseus, his flying horse Pegasus, the hideous Medusa, and the sea monster Cetus, all of whom have been immortalized as constellations. I could have related this greatly interesting story, but as we have noted, time is in short supply. I am certain that *signore* will grace the celestial realm again on some other occasion and it will be my unbounded pleasure to narrate the aforementioned tale.'

While Casanova was busy telling me about the various constellations, I noticed something strange happening. Cassiopeia stood up and started walking majestically away from her throne. As though following her example, all other figures detached themselves from the constellations they represented, and started moving in the same direction as the Queen.

'I agree with the *signore* that what he is beholding is indeed a vision most puzzling and perplexing, confusing and confounding,' said Casanova with a light laugh. 'Please allow me to demystify you, *signore*. This is the night Orion the great hunter and his mortal enemy Scorpio re-enact their epic battle. And all the denizens of the celestial sphere are proceeding to witness this drama, which is repeated once every year. Please allow me to explain further, if I may,' offered Casanova. 'Orion is the celestial hunter who holds aloft a lion's skin as a shield. A lion's skin for a shield? What kind of protection it might provide against any weapon except pebbles pelted by a child is beyond my comprehension. Be that as it may, our hero proved the veracity of the age-old cliché that brawn and brains are mutually exclusive. How?, you may venture to ask. Well, by boasting to Artemis that he was strong enough to wipe out all the animals that inhabited the Earth. Artemis, of all people, who happens to be the goddess of animals! She was alarmed, to say the least, and so was the Earth goddess Gaea. The latter sent a huge scorpion to slay Orion once for all. Once for all? How many times, I ask you, could one slay a single individual? In the mortal combat that ensued, the astral arachnid eliminated the celestial hunter with its venomous sting. The two combatants were immortalised as two constellations placed at opposite sides of the celestial sphere so that they never appear together. Nevertheless, once a year the two opponents come together, and re-enact their battle for their own edification, and also for the entertainment of others. Tonight is the night of such an encounter. We shall watch it soon enough. But there is time to visit three astronomers of renown, who were fortunate enough to witness three different stellar explosions.'

'During our visit,' informed Casanova after a pause, 'you will obviously hear all the conversations in your own language. Instantaneous, automatic translation, shall we say? I shall fill in the details whenever necessary. Remember too, that when we travel back to the past, time gets smeared out, with people moving back and forth over the years. But all this will be within a fixed time frame, going not too far back into the past, nor too much further into the future. Prepare yourself physically and mentally, *signore*, as we first travel in space and time to ancient China, to Khaifeng, the capital of the Sung Dynasty. It is July 4, 1054 AD, according to our calendar. Just before dawn. We gaze upon the learned astronomer Yang Wei-Te as he discourses to one of his apprentices.'

The scene shifted to a spacious room, which was part of an astronomical observatory. On several tables lay elaborate records of astronomical observations in neatly arranged stacks. On one side stood a beautifully crafted, bronze replica of an armillary sphere composed of a number of circular rings and supported by four upright dragons, each balanced on one of its hind legs. This was an instrument used to determine the position of a star with respect to the celestial North Pole. Close to it was a clepsydra or water clock, which was extremely important in timing celestial events. Placed against the wall were scale models of two towers, one that was used for determining the lengths of the shadows cast by the Sun and the other that housed the huge water clock of high accuracy. Hanging from a simple frame was a circular bronze disk, one side of which had been polished to serve as a mirror. On the other side, constellations and symbolic figures of animals had been carved in concentric circles. On the outer ring appeared the inscription of an ancient poem, which spoke of the universal harmony between the regularities of the heavens and the tranquillity of the Earth.

Seated on a lacquered stool was Yang Wei-Te, the Court Astronomer. Facing him was a young man, kneeling behind a low table, which held writing materials. He was an apprentice and scribe appointed by the state, as were all the astronomers. Fortunately, priests had no role to play in this sphere of activity. The Court Astronomer was explaining to the young man the duties of an astronomer and his assistants. All through the night, they had to watch the night sky, charting the course of the celestial objects and looking diligently for unusual events, such as the appearance of comets. Astronomers also had to predict the occurrence of eclipses. According to legend, two astronomers Hi and Ho had been executed, some three thousand years earlier, for failing to predict and warn of an eclipse. A gross exaggeration perhaps, since in antiquity, long ago, there was no way they could have made such a prediction. In any event, no punishment had been meted out to astronomers in recent times on account of their lapses. Nevertheless, astronomy was paramount to the functioning of the Emperor, the Son of Heaven. While the stars dictated his course of action, his own behaviour, in turn, influenced the motion of celestial objects like the Moon.

Yang Wei-Te looked out of the window. It had been a clear and calm night and soon it would be dawn. He could still see distinctly the diffuse band of light stretched from horizon to horizon, *thien ho*, the River of Heaven. The stars were shining and he knew them all like life-long friends. Suddenly, Yang Wei-Te sat up, startled. In the eastern sky shone a brilliant star that he had never seen before. It was a 'guest star', which was tinged with yellow, the imperial colour. This was a portent that the country would flourish and gain great power. The young scribe, who was also excited by this good fortune, noted down the event, which would later be transferred to the court records. Yang

Wei-Te's heart filled with joy as he contemplated how happy his tidings would make the Emperor.

The guest star would shine as brightly as the planet Venus for twenty-three days and would remain faintly visible even during daytime. It took nearly two years for it to fade from view completely. Witnessing this rare event was undoubtedly the greatest moment in the life of Yang Wei-Te.

'Observing the *nova*, the new star of 1572, was the greatest event of my life, which led me to dedicate myself to the divine pursuit of observing the heavens and recording the positions of the celestial objects,' the older of the two men seated at an ornately carved table was telling his younger companion.

The transference from ancient China to what appeared to be Europe of a few centuries ago was instantaneous, and rather disorienting. Casanova regarded me with amusement as he commented, 'Ah, *signore*, we have moved with the speed of thought, which knows no bounds, unlike that of ponderable matter. The effect can be most disconcerting to ordinary mortals, for which no pardon need be sought.'

I ignored this last remark, as I saw no reason to be apologetic about my own personal state of mind. Casanova now spoke with obvious reverence in a hushed voice.

'We are in the presence of two great astronomers, *signore*. The one who spoke just now is Tycho Brahe, the King of Observers, and the other one is Johannes Kepler, who is celebrated for his three laws of planetary motion, among other things, as you would certainly know. We have come to Tycho Brahe's observatory, Uraniborg, or the Palace of Astronomy, which is situated on the island of Hven outside Copenhagen and is dedicated to Urania, the Muse of Astronomy. Kepler never worked with Tycho Brahe here, but only later on in Prague, as Tycho Brahe's assistant. Nevertheless, as I told you before, time has been smeared out and Kepler himself has been moved into a past era. Listen to the two great astronomers, *signore*. Often what is spoken happens to be quotations from what has been written, which may sound literary and archaic unlike the rest of their ordinary conversation.'

Befitting his position as a hereditary nobleman, Tycho was dressed in the finest clothes fashioned out of silk and velvet. An intricately designed medallion hung from a golden chain that he wore around his neck. Whereas others belonging to nobility pursued traditional professions, astronomy had become the all-consuming passion of Tycho's life. Curled up at Tycho's feet lay his faithful hunting dog, yawning from time to time, bored as it was with the conversation going on over its head. I noticed something strange about Tycho's nose, which had a dull sheen to it.

'I perceive that *signore* has noticed Tycho Brahe's nose,' Casanova observed with relish. 'It glows strangely, for it has been constructed out of gold, silver and wax – an admixture of two noble metals with the ignoble produce of an insect, I must say. Tycho Brahe himself designed it. "Whatever happened to the original nose made of flesh and blood?" you may make yourself so bold as to ask. And I shall oblige you with the answer. The God-given olfactory organ was severely damaged in a duel Tycho Brahe fought with his third cousin. A duel fought over the amorous attentions of a dainty damsel perhaps? Alas, no. Swords were crossed on account of an argument that broke out at the dinner table of a Professor, as to who was the better mathematician, Tycho Brahe or his third cousin! "Can there be anything more preposterous than a duel over such an academic altercation?" I ask you. Let me hasten to add that you need not tax your brains for an answer, because the question was, as they say, purely rhetorical.'

I could see in the background a variety of astronomical instruments: quadrants ranging in size from a radius of sixteen inches to seven feet; sextants; armillary spheres; and several other observational aids. With the help of these one could measure the location of celestial objects with the utmost precision. I noticed something else, which was most extraordinary, and had previously escaped my attention. Seated beneath the table, where the two astronomers sat, was a dwarf chattering away incessantly to himself.

'Ah, that is Jeppe, Tycho Brahe's pet dwarf,' explained Casanova. 'Pray tell me, how many of your astronomers keep pet dwarfs, *signore*? Tycho Brahe feeds Jeppe morsels from his table and, believe it or not, takes his advice on the affairs of Hven, which Tycho administers, because Tycho is convinced that the dwarf is blessed with prescience. On one occasion, when the peasants of Hven had been insubordinate, Jeppe counselled that they be assembled and offered all the beer they could drink instead

of being punished. Alcoholic amelioration of administrative ailments! Sound advice, if you ask my opinion.'

'I still remember vividly the momentous occurrence on the eleventh day of November in the year fifteen hundred and seventy-two,' Tycho continued his reminiscence. 'I was returning from my little laboratory, where I had been conducting some chemical experiments. It was evening, after sunset, when according to my habit, I was contemplating the stars in a clear sky, I noticed that a new and unusual star, surpassing all the other stars in brilliancy, was shining almost directly above my head; and since I had almost from boyhood known all the stars of the heavens perfectly, there is no great difficulty in attaining that knowledge, it was quite evident to me that there had never before been any star in that place in the sky, namely in the constellation Cassiopeia, even the smallest, to say nothing of a star so conspicuously bright as this. I was so astonished at this sight that I was not ashamed to doubt the trustworthiness of my own eyes. But when I observed that others, too, on having the place pointed out to them, could see that there really was a star there, I had no further doubts. A miracle indeed, either the greatest of all that have occurred in the whole range of nature since the beginning of the world, or one certainly that is to be classed with those attested by the Holy Oracles.'

'Like most astronomers of his age, Tycho Brahe believed in astrology,' Casanova informed me. 'Even in your own time, there are some astronomers, I am sure, who do so. But let us listen to what Tycho Brahe has to say about the prophecies of the new star.'

Tycho went on to describe the astrological implications of his *nova*. 'The star was at first like Venus and Jupiter, giving pleasing effects; but as it then became like Mars, there will next come a period of wars, seditions, captivity and death of princes, and destruction of cities, together with dryness and fiery meteors in the air, pestilence, and venomous snakes. Lastly, the star became like Saturn, and there will finally come a time of want, death, imprisonment and all sorts of sad things.'

'None of which came to pass of course,' interjected Casanova. 'But that is not the end of the story – as we are about to learn.'

'I assume that you are aware of all the speculations and the furore that followed in the wake of the *nova*?' Tycho asked Kepler.

'I have heard about it,' answered Kepler, 'I was only a year old at the time.'

In striking contrast to Tycho, Kepler wore modest clothes. He had a wan look, as though dogged by constant illness. Nonetheless, his eyes were bright and penetrating, reflecting an exceptionally keen intellect.

'Followers of John Calvin, the theologian, went so far as to proclaim that it was a second star of Bethlehem, heralding the second coming of Christ on Earth,' recalled Tycho. 'But the crucial question was whether the *nova* belonged to the realm of the stars. This would have contradicted Aristotle's dictum that the celestial region is eternal and immutable. Or did it belong to the sub-lunar world of changeable earthly elements? Was it perhaps a comet condensed from ethereal vapours or from fumes of human sin as some imagined? I put an end to all those inane conjectures, did I not?' Tycho paused to savour the memory of his triumph and continued. 'I had to make repeated measurements of the position of the *nova*, its distance from the celestial pole, to show that it was indeed a star and not an inhabitant of the sub-lunar region, thereby contradicting the cherished ideas of Aristotle. But what was this strange new star made up of? I believe that it was formed out of celestial matter, but of less perfect variety than that of normal stars and thus it gradually dissolved away.'

Tycho stroked his beard as he mused about the days of his glory.

'I wrote down all my findings in my book *De Stella Nova*, On the New Star, a masterpiece, many said afterwards. Deciding whether to write that book or not was a struggle for me, for many a nobleman of my acquaintance felt strongly that writing a book was an occupation beneath my rank. Nobility has its own norms and manners, you know.'

A serious look came over Kepler's countenance as he remarked, 'I know that very well! I remember the occasion on which you accompanied one of the Royal Councillors to supper. Although you drank a bit overgenerously and felt pressure on your bladder, you had less concern for your health than for your manners, and remained seated at the table. By the time you returned home, you could no longer pass water.'

Jeppe the dwarf suddenly jumped up and screeched, 'From Urania to uremia, from Urania to uremia!' and cackled loudly. Kepler, wanting desperately to get out of this awkward situation, hastened to change the subject.

'In the year 1604, three years after you left for your Heavenly Abode, I too was fortunate enough to discover a *nova*. Its location was in the constellation Ophiuchus who holds in his arms the serpent, the constellation Serpens. It caused a great deal of excitement, because it coincided with the rare conjunction of Mars, Jupiter and Saturn which occurs only once in eight hundred years. I was also able to demonstrate that the *nova* belonged to the region of the stars and not to the vicinity of the Earth. Again, one more blow to Aristotle's philosophy.'

'That is not all,' Tycho said excitedly. 'Five years after the appearance of the *nova* in 1572, I observed a comet and proved that it was far above the Moon and had started its journey way beyond the planet Venus. Aristotle had claimed that each planet was fixed in a crystal sphere that turned making celestial music, had he not? If so, the comet in its journey ought to have shattered the crystal spheres. Did we hear the tinkling sound of the falling shards of crystal? Oh, no, and why not? Because the crystal spheres in all probability do not exist at all. Often, people who watch the sky never think of the implications of what they observe. That is why I rebuked them in my book on the new star with the words, *O crassa ingenia, O coesa coeli spectores* - Oh thick wits, Oh blind watchers of the sky!'

'Aristotle thought that the sun and the planets circled around the earth imbedded in their crystal spheres, and Ptolemy gave a fine but complicated model of this Earth-centred universe. But we know that the planets go around the Sun, do we not?' added Kepler.

'Yes, but what about the Earth?' asked Tycho. 'According to Copernicus, the Earth goes around the Sun too. I think not, for the Earth is a hulking, lazy body unfit for motion. Look at my beautiful model of the universe in which the planets move around the Sun, and the Sun, along with the planets, revolves around the fixed Earth.'

Kepler was silent. He knew that Copernicus was right. Yet, one had to admit that Tycho's model was the same as that of Copernicus but as viewed by an Earth-bound observer. It just complicated matters unnecessarily.

'I wanted you to prove my model,' continued Tycho. 'That is why I set you on to my observations on Mars from which I expected you to deduce its orbit.'

Kepler's eyes became distant as he thought back on the past. His voice was tinged with gratitude as he spoke.

'In answer to the letter I had written in 1597, you mentioned, among other things, your observations, which fired me with enormous desire to see them. From then on you became an important part of my destiny, continually urging that I should come to visit you. But the distance of the two places would have deterred me. I ascribe it to Divine Providence that you yourself came to Bohemia, where I happened to be at that time. I thus arrived at Prague at the beginning of 1600 and you authorized me to use your observations. At that time your personal assistant, Christian Severinus Longomontanus, had taken up the theory of Mars. Had Christian been studying another planet, I would have started with the same one also. That is why I again consider it an effect of Divine Providence that I arrived in Prague when he was studying Mars. Because for us to discover the secret knowledge of astronomy, it is absolutely necessary to use Mars. Otherwise, that knowledge would remain eternally hidden.'

'You anticipated that you would complete the calculation of the orbit of Mars in eight days,' Tycho pointed out. 'How long did it take in the end?'

'More like eight years,' Kepler smiled. 'Vanquishing Mars, the god of war no less, was an immense task. But what a revelation to discover that the orbit was an ellipse and not a circle as had been believed since antiquity! And Mars did not move with uniform velocity either. He speeded up near the Sun and ambled slothfully far away from the Sun when the latter's influence on him diminished.'

'Did you ever think of the physical causes that control the planetary motion?' enquired Tycho.

'Indeed I did,' Kepler responded. 'My goal after all was to show that the celestial machine is not so much a divine organism but rather a clockwork as much as all the variety of motions are carried out by means of a single, very simple magnetic force of the body, just as in a clock all the motions arise from a very simple weight. The Sun is the fountain of strength, a great magnetic body, whose rotation also turns the magnetic emanations that propel the planets in space.'

'On the other hand, some believed that the angels push the planets around.'

'I feel that the subtle reflections of some people in regard to the blessed angels do not concern us. We are discussing natural matters of much lower rank.'

'Well, I wish I had lived long enough to see the fruits of your labour, which was, after all, based on my observations.'

'So do I, for the reason that, six years after you were freed from earthly shackles, the Italian philosopher Galileo Galilei introduced his glazed optical tube, or telescope as it has come to be known, to astronomy. He made astounding discoveries with its aid. Incidentally, he too sighted the two different new stars we had observed. I cannot imagine what marvels you might have unravelled with the use of the optical tube.'

'Did you ever employ that instrument for your own observations of the heavens, Johannes?'

'I wrote to Galilei entreating him to send me an optical tube, but he sent me only his book. The Duke of Bavaria lent me one for just five weeks and took it back promptly thereafter.' Kepler's regret of having missed the use of the telescope was evident.

'I understand that Galilei, because of his observations with his optical tube and moreover because of his staunch adherence to the Sun-centred universe of Copernicus, ran into conflict with the Catholic Church, and had to recant his beliefs under the threat of torture. Most unfortunate indeed.'

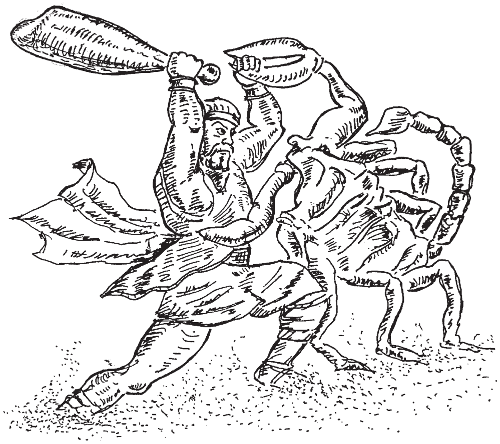
Kepler was passionate: 'That was truly tragic. While in theology it is authority that carries the most weight, in philosophy it is reason. Therefore, Lactantius is holy who denied that the Earth is round; Augustine is holy who, though admitting the roundness, denied the Antipodes; and the Holy Office nowadays is holy which, though allowing the Earth's smallness, denies its motion. To me, however, the truth is more holy still, and with all due respect to the Doctors of the Church, I prove philosophically not only that the Earth is round, not only that it is inhabited all the way round at the Antipodes, not only that it is contemptibly small, but also that it is carried among the stars.'

Tycho closed his eyes in thought. 'We all strive to find the truth underlying what we see. How far we succeed it may not be given to us to decide and often not even to know.'

Kepler fell silent for a moment and recalled with a touch of sadness. 'During the last night of your life, you kept whispering again and again: *Let me not seem to have died in vain*.' And then he added with emphasis, 'There was no need for such thoughts. You were and will always be the King among Astronomers, Master.' The two men fell silent, each wrapped in his own thoughts.

The scene gradually melted away. 'Two great astronomers,' exclaimed Casanova. 'Yet, they knew not the agency that impelled the planets to move around the Sun with such order and precision. Nature imparts knowledge to man in small portions much as a bird feeds its young. Decades had to pass before the basic mechanism of planetary motion was revealed in all its glory, opening up an entirely new chapter in human history. Ah, let us forget philosophy, *signore*, which turns one's hair grey, and kneads the brain into batter. It is time now to witness the battle between man and beast, between Orion and Scorpio. Let us go.'

Having visited the three astronomers, who had observed three different supernovae that had exploded in our own galaxy, we moved on to the venue of the impending combat between Orion and Scorpio. A large crowd had already gathered, consisting of the beasts and the mythological characters after whom the constellations had been named. Standing upright on its hind legs was the big bear, Ursa Major, carrying on its shoulders the cub, Ursa Minor. Later on, whenever the fight had its moments of excitement, the cub would drop down, curl up into a ball and roll around before getting back onto its perch. Draco, the dragon was around. Throwing its head back and opening its mouth wide, it emitted long jets of flame from time to time. Close by was the immense giant, Hercules, who kept mumbling throughout the fight about his own exploits. Here was pitiable Orion, who was unable to finish off a lowly scorpion, whereas he, the mighty Hercules, would have squashed the insect under his little toe in no time. Next to Hercules, stood Ophiuchus holding his serpent, which hissed rudely whenever one of the combatants made a false move. There were many onlookers waiting eagerly for the event to start. Pre-eminent among them with her dazzling presence was Queen Cassiopeia.



At the centre of it all, stood the two antagonists. Orion's body, rubbed with fragrant oils, glistened in the starlight. He tested his enormous club for balance and smashed it on a nearby rocky asteroid, which crumbled into shimmering dust. Scorpio was flexing four of its rear legs, while with the two front ones it was stroking its pincers. In a moment, trumpets blared out from the zenith, where the invisible gods had probably gathered to watch the spectacle below. Then the mortal combat began. The two opponents sprang into action. After a few rounds of evenly matched tussle, Orion brought down his club heavily and immobilised one of Scorpio's pincers. The creature shrieked hideously in agony and rage. With a swift move, it knocked off Orion's club, which flew far away into space gradually vanishing from sight. It was now a trial of strength between Orion's two hands and Scorpio's single good pincer, which the hunter was trying to twist off. As he strained with all his might, rivulets of sweat ran down Orion's muscles as they rippled and trembled. All of a sudden, the scorpion moved sideways ever so slightly, throwing its opponent off balance. Like a flash of lightning, its tail lashed out and stung the hunter on his side, who collapsed with a frightening wail. He thrashed around for a few moments and then lay still. Scorpio let out a roar of triumph, while the crowd froze in stunned silence. Ophiuchus rushed to Orion's side, took out a piece of herb from the embroidered satchel that hung by his side, and wrung its juice onto the prone figure of the hunter. Likewise, he rubbed the herb on Scorpio's paralysed pincer, curing it instantly. Orion sat up, shook his head as if coming out of a daze, and finally stood up. The crowd broke out in thunderous applause. The invisible trumpets let out another long blast. And the two combatants bowed deep to each other and to the crowd. Then they drifted away in opposite directions. The onlookers departed too, going back to their own respective constellations, slowly fading away.

'Well, *signore*,' Casanova spoke to me with a warm and straight smile. 'I hope you enjoyed our little shadow play.'

He looked serene and a little sad as if he had suddenly grown old. There was again the background music playing far away.

'The mind is a strange crucible where the past, present and future mingle with what you have learnt, what you have thought and what you have imagined, creating new visions, characters and events. Like conjuring up Casanova out of an exploded star, and making him act as the guide, which I assure you was an immense pleasure. But the time has come for me to take leave of you. May peace be with you! We shall see each other soon. Or, as we say in Italian, *ci vediamo, a presto, signore*!'

Like a waking dream, Casanova dissolved into space as the music too faded away. And so did the stars, one by one, leaving me alone in the engulfing darkness.

I opened my eyes. The bath water had become lukewarm. The bubbles had evaporated. I got up, dried myself, went to bed and soon fell into a dreamless sleep.

Chapter 4

FOOTPRINTS OF THE GIANTS

These last few days have been intoxicating. I needed a break. So I packed up and went to this remote, un-spoilt spot by the sea and camped out there. I wanted to bask in the sun and let myself be enclosed within the cocoon of warmth and light. I wanted to feel the salt-laden spray on my skin. I wanted to breathe deep the fresh air as nature made it, untainted by human folly. Oh, yes, I took along a rucksack filled with books on Isaac Newton and his predecessors. I had planned to build up my background for the discussion I was going to have with George on Newtonian gravity.

Each morning I was greeted by the sea, that vast uncut emerald set in the shimmering sand. In Spanish, the sea is both feminine and masculine, *La Mar* and *El Mar.* It was the beautiful *La Mar* that gently caressed the earth who had surrendered to her. Wave after soft wave swept over the recumbent figure.

Each evening nature unwove the rainbow and painted the sky with a hundred hues. The setting Sun stooped down to kiss his children goodnight, the shadowed earth and the rippling sea braided in gold. Soon, the Moon appeared with her silver smile. The sea was now transformed into *El Mar*, seething in a frenzy of tidal waves crashing against the dark crags, as it raged in unrequited love for the distant Moon.

The golden Sun and the silvery Moon. I remembered the lines Yeats had written:

And pluck till time and times are done
The silver apples of the moon,
The golden apples of the sun.

Silver apples dropped from the Moon and the golden apples fell from the Sun. And gravitation was born.

On the last day of my stay, I strolled along the edge of the sea, taking care not to disturb her serene tranquillity. Some children were busy building castles in the sand. At a distance stood a frail, little boy, all by himself on the seashore, intently searching around. As I passed him, he smiled at me and held up his open hand. Nestling in his palm were some exquisite pebbles and shells he had collected. By the time I returned from my long walk, the children were gone. The steadily advancing sea would soon wash away the sand castles, while in all probability the lone child played on with his treasured collection all by himself.

I was to meet George in the University Park, which is tucked away in a corner of the campus. Elegantly landscaped, the trees, the shrubs and the lawns of this little park form a harmony in colours, structures and textures. Although meticulously maintained, it has a natural intrinsic beauty that makes it pleasantly comfortable. There are several benches beneath the trees. They are often occupied by students preparing for their classes, members of the faculty discussing university affairs, or just young couples holding hands. I sat on one of those benches and waited for George, taking in the atmosphere of the academe in its finest setting.

I could see George at a distance hurrying towards me for our meeting. His unbuttoned jacket was flapping from side to side revealing all the papers he had stuffed into his inner pockets. He was clutching close to his chest a large volume and in his other hand he carried a writing pad.

George sat down next to me, planting between us the big book he was carrying. He mopped his brows with his handkerchief and sighed deeply.

'Sorry to have kept you waiting, Alfie,' apologized George. 'I was held up by this undergraduate who is in a dilemma.'

'What kind of dilemma?' I asked.

'He wants to do physics. But his parents would like him to go into medicine, which is much more lucrative.'

'Even Galileo had the same problem, didn't he, George?' I recalled from my readings about the great scientist. 'His father Vincenzo would have preferred to see him become a professor of medicine in the university rather than a professor of mathematics. Simply a matter of two thousand *scudi* per year as against a measly sixty. Nothing to pooh-pooh at! '

'Thank God, Alfie, there isn't that kind of disparity in our salaries within the university system any more.'

'Anyway, the story goes that Galileo managed to study Euclid and Archimedes on the sly, hiding them underneath his Galen and Hippocrates.'

'Yes, things haven't changed that much in all these centuries. At least Galileo's father had the good sense to give in, unlike many parents nowadays.'

'But look at Kepler, whose situation was strangely different,' I went on with my recollections. 'He wanted to study theology and become a Lutheran minister. The poor guy was forced to learn and teach astronomy for a living.'

'Lucky for astronomy! Kepler had nothing to do with medicine though.'

'No, unless you consider his incurable hypochondria as indirectly related to medicine, you know. Apparently, through out his life, Kepler suffered from all sorts of maladies, both real and imaginary. Believe it or not, he chronicled the whole lot: smallpox, skin ailments, sores, a worm in his finger – whatever that may be – headaches, so on and on. Poor man tried everything he could think of to heal himself. Unlike Kepler and Galileo, Copernicus happened to follow all three vocations, right?'

'How do you mean?'

'He was an astronomer all right,' I pointed out the obvious. 'And he studied theology and became a canon in the church. Then again, he was also educated as a physician and even practiced traditional medicine. There is a record of a prescription that he jotted down. It calls for, among other things, shavings of ivory, emeralds, sapphires, deer's heart bone, beetles and – would you believe it – powdered horn of a unicorn! You would never guess where he wrote it down.'

'Where?'

'On the back of a copy of Euclid of all places!'

'You seem to have read a lot about those astronomers during your vacation,' remarked George, half grudgingly. 'Lucky you, Alfie. Taking off whenever you want. And reading whatever you want.'

'Let me admit it: It was really great, George. Copernicus, Galileo and Kepler. They were real giants, weren't they? They don't come in bunches like that always.'

'You are right, Alfie! Even a school kid knows Newton's famous remark: *If I have seen further than others, it is by standing upon the shoulders of Giants*. But Newton was the greatest giant of them all.'

'Well, the poet Lucan in the first century AD said that a dwarf standing on the shoulders of a giant can see farther than the giant himself! How do you like that?'

'What do you know! Some of us dwarfs may still have some hope after all,' chuckled George. 'Now that you have mentioned those three heavyweights who preceded Newton, why don't we talk a bit about them?'

George was silent for a while as he drummed the side of his chin with his forefinger thoughtfully.

'You know, Alfie, those three men radically changed the way we look at nature. They dismantled the old order that had endured for more than two millennia. And established a new one too.'

'Wait, the old order according to Aristotle, you are talking about. Right?'

'Yes, I suppose you know all about it.'

'Well, I did read some books on early astronomy and the Copernican revolution. All along, I got this funny feeling that poor Aristotle was looked upon as the villain in the piece. He said this, he said that! All wrong things. Led us up the garden path. So on and so forth. After all, Aristotle was a great thinker, wasn't he, George? I believe he was trying to explain what he saw as best he could. He saw the stars fixed in the same beautiful patterns night after night. So he concluded that the heavens were immutable. He watched the celestial objects move around him and came to the obvious, simple conclusion that they revolved around the immobile Earth.'

'Fixed in crystalline spheres no less!'

George was smiling, enjoying this dialogue. Sometimes he treated me like an equal sparring partner, and sometimes like a little child. On my part, it was fun playing the Devil's Advocate for Aristotle.

'Why not? How could planets float around in space without some kind of stable support? So, each planet was fixed in a transparent, crystalline sphere turning around the Earth and making divine music. With the stars fixed in the outermost sphere, the *primum mobile*, the Prime Mover. Beyond it was the *Empyrean*, the abode of the gods. The gods, or God Himself, cranked the shaft that turned the crystal globes. It is so poetic that Dante made this cosmos the central setting for his *Divine Comedy*.'

'Poetic all right. But the model didn't offer any quantitative explanation for the planetary motions.'

'But, George, that was left to Ptolemy and his geocentric model that described the planetary system in detail. Am I right?'

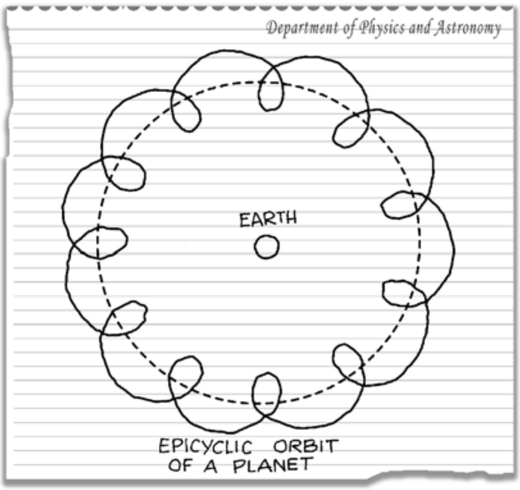
'Right. But the model was too complicated with all its epicycles!'

'Epicycles? What are they?'

'Well, as seen from the Earth, the planets, blissfully moving along their paths, sometimes seem to go backwards, make a loop and proceed again in their original direction. This is known as retrograde motion.'

'So?'

'So, a planet was assumed to move not along a simple circular orbit, but along a smaller circle rolling on a larger circle. This little circle is known as an



epicycle. The effect was to generate loops along what should have been a simple circular orbit. And, the planets were assumed to be actually making these loops.'

George sketched the loops generated by the epicycles on his writing pad.

'The end result was that the planetary orbits contained lots and lots of epicycles, so much so that the geocentric scheme became awfully complicated.'

'Aha, this is where I come into the picture!'

'What do you mean *you* come into the picture? How do *you* figure in all this?' George seemed to be a bit baffled by my statement.

'How do I come into the picture? Well, through my illustrious namesake and probably my forebear.'

'I know that you have a rather unusual name, Alfonso L. Sabio,' said George. 'But, who was your illustrious forebear? Alfie, stop talking in riddles.'

'Alfonso el Sabio, Alfonso the Wise, the thirteenth-century King of Castile and Leon in Spain,' I replied. 'You know what he said when he was shown Ptolemy's model of the universe? *Had I been present at the Creation, I would have recommended something simpler to the Lord Almighty!*'

George laughed at this statement and held up his forefinger in a gesture of making an important point. 'Alfonso was absolutely right, although I doubt that he was your illustrious ancestor. Simplicity is the corner stone of all science. Every theory strives to achieve simplicity and beauty.'

'As they say in Latin, *simplex sigillum veri*: The simple is the seal of the true. And, *pulchritudo splendor veritatis*: Beauty is the splendour of truth.'

'That is what Copernicus discovered. The simplicity and the beauty of truth, when he demanded that the Sun stand still while the planets, including the Earth, circled it,' said George.

'I thought Aristarchus of Samos said as much as far back as the third century BC,' I pointed out.

'True. But, Alfie, it was Copernicus who developed this idea into a quantitative model of the Solar System. One of the most important aspects of this heliocentric model was that it explained the retrograde motion in a simple and natural way. The combined motion of the Earth and the planet produced the illusion of the planet making a loop.'

'I sort of glanced at *De Revolutionibus Coelestium Orbium* by Copernicus, which is supposed to be one of the most unreadable books of all time, you know. I couldn't make out much of it. But I do remember the description Copernicus gives of his new cosmic order in his book. It is so beautiful, George.

> *In the middle of all sits the Sun enthroned. In this beautiful temple could we place this luminary in any better position from which he can illuminate the whole at once? The Sun sits as upon a royal throne ruling his children, the planets which circle round him.'*

'That is so poetic. Scientists in the good old days wrote so well. Nowadays we hardly ever pay attention even to the grammar when we write our papers.'

'Another thing, George. When you learn about the heliocentric model in school, you are never made to realize the overwhelming importance of the Copernican revolution.'

'I know, Alfie. The Earth is enormous. This had been known since antiquity. To consider it to be spinning like an ordinary top and then to assume that it merrily waltzes around the Sun! It was a phenomenal leap of imagination. It was a passage from appearance to reality.'

'Let me tell you how Galileo puts this idea across in his book *Dialogues on the Two Chief World Systems, Ptolemaic and Copernican.* He speaks through Salviati, one of the three characters engaged in the dialogues. The one who represents Galileo himself. He says,

> *There is no limit to my astonishment when I reflect that Aristarchus and Copernicus were able to make reason so conquer sense, that in defiance to the latter, the former became the mistress of their belief.'*

'Beautifully put!' George said with feeling. 'And Galileo should know. After all, he was one of the earliest champions of the Copernican ideas, you know. He buttressed the Copernican model enormously. With his little home-made telescope he revealed so much of the universe! He discovered the mountains on the Moon and observed the spots on the Sun. Which meant there was nothing heavenly about them. They were just like our own Earth. He discovered the four satellites of Jupiter. Which showed that there was nothing special about the Earth either. Earth was not the only centre of revolution. All celestial objects including the Earth were similar in nature. Why shouldn't the Earth go round the Sun then? All this did so much to establish the Copernican order of the cosmos.'

'And in the bargain, Man lost his central position in the universe.'

'Yes. And once the Earth was set in motion, what happened to the confining crystal spheres of Aristotle? They crumbled out of existence. The universe could be immensely large or even infinite. Copernicus himself had conjectured that the stars were at enormous distances from us. That meant the *primum mobile* was gone. The *Empyrean* was banished. Where would you place God then?'

'No wonder the Church looked upon Galileo's *Dialogues* as anathema. One of the greatest books ever written! Bringing old Galileo to trial, intimidating him with the prospect of torture and making him recant – can you imagine anything more horrible?'

'I agree, Alfie. And Galileo's last days were so tragic. He was practically under house arrest. In spite of growing blindness, he wrote his monumental volume, *Dialogues Concerning Two New Sciences.* The book had to be smuggled out of Italy, Alfie. It was the result of Galileo's experiments carried out over more than thirty years, you know.'

'Lot of these experiments had been performed using inclined planes. Weren't they?'

'Yes indeed. For instance, he rolled a ball down an inclined plane and let it continue its journey on a horizontal surface. The smoother the surface, the farther the ball went. This gave Galileo the idea of inertia. If the surface were infinitely smooth, the ball would roll on forever. Also the inclined plane diluted gravity so to speak. And he could study falling bodies more easily by rolling them down the plane rather than dropping them from a height. Galileo's experiments and his book launched the science of mechanics.'

'You know what the French philosopher Henri Bergson said? *Newtonian physics descended from Heaven to Earth along the inclined plane of Galileo.*'

'Ah, that *is* lovely imagery, Alfie!' George was truly impressed.

'So much for Galileo. What about Kepler? How does he fit into the overall picture?' I asked.

'All right, let us talk about Kepler then,' George said. 'As you know, Galileo and Kepler were contemporaries. Both were great men. But each had his own approach to science. Galileo did his work with a sweep, with insight and intuition, not worrying about the details. Kepler, on the other hand, was highly mathematical and precise. Look at his three laws of planetary motion. It took tremendous industry and care to discover them. By the way, with his elliptical orbits, Kepler removed the epicycles completely. They had persisted even in the Copernican model.'

'Why is that?'

'Because Copernicus had assumed that the planets moved in circular orbits with uniform velocities. Vestiges of the Platonic ideal, you know. All the same, without the Sun at the centre Kepler might not have discovered his laws. By the way, do you know how Kepler discovered his third law, which relates the orbital period of the planet to the size of the orbit?'

'No, how did he do it?'

'Kepler, who firmly believed in the harmony of the planetary motion, tried to fit each of the orbits to different sets of musical notes. In this process he discovered his third law.'

'Aha, Aristotle was right after all! Music of the spheres does exist then.'

'Well, you are right in a way I suppose,' conceded George.

'In any case, Kepler indirectly proved the heliocentric theory of Copernicus, didn't he?'

'Yes and more. Three laws, and only three, described all planetary motion. And motion of satellites like our own Moon and the moons of Jupiter. So the age of laws on a universal scale had dawned.'

George let out a deep sigh.

'So finally what do we have, Alfie? The Sun stands still with the planets trooping around it followed by the entourage of their own moons. All their motions precisely ordained by just three laws. And the science of mechanics introduced to the world. What does it all mean?'

'It means that we are ready for Sir Isaac Newton,' I answered.

'It also means that I am hungry and ready for a bite. And I am sure, so are you. Let's go.'

I deposited George's big book and his writing pad with the utmost care in my backpack and we set off for our lunch. Of the many university campuses I have seen, this one happens to be the best. It is surrounded by gently rolling hills interspersed with lush vegetation. Buildings appear to be part of the picturesque background, the new constructions designed to blend with the venerable old ones. The large central courtyard is the hub of all outdoor activities, especially after working hours. Here, students play music, dance around, and occasionally give short skits as impromptu performances. There are also a few eating places, mostly run by students who want to earn some extra money.

'A light lunch to offset the heavy discussions we are having, what do you say, Alfie?' said George as he led me to a quaint little kiosk.

'The kid selling sandwiches is Andre Lubinski, a student of philosophy of science,' George informed me, and addressed Andre.

'Hi, Andy. This is Alfie here, a real gourmet. What is special today?'

'Try our homemade kielbasa sandwich, the letter 'l' pronounced like in between 'l' and 'w'. Don't ask me whose home it was made at.'

'What is kielbasa?' George enquired.

'It is a spicy Polish sausage. The original Polish sausage with garlic in it. Keeps the vampires away, you know.'

'You've got vampires in Poland? I thought they lived, or should I say were dead, in Transylvania.'

'Long ago Polish kings were chosen by election,' Andy explained. 'We imported one from Hungary whose daughter turned out to be a famous – or rather, infamous – vampire. So kielbasa with garlic was invented. Great with fried onions.'

'All right. Two to go with your fresh orange juice. How did you do on your term paper by the way?'

'Got an A plus.'

'What was the topic?'

'*A Critique of Reichenbach's and Carnap's Philosophy of Geometry*.'

'Heaven help me! I can't make head or tail of even the title. Keep it up, Andy.'

We sat down with our brown bags of lunch at a nearby table made of rough slats of wood.

'You know, Alfie, some of these kids like Andy work very hard to get into the university. And they have to keep working hard to stay on in the university too,' commented George.

'Age-old story if you ask me. Even Newton had the same problem in the beginning,' I remarked.

'How come?' George queried.

'Newton had little money when he joined Trinity College at Cambridge. He became a Sizar, a student who paid his way through college by doing odd jobs and by waiting on his tutor.'

'Thank God, our students don't have to do that.'

'Later on, he became a Fellow when vacancies opened up. You know how? A Senior Fellow had been sent away from the college on account of insanity, and two others because they had unceremoniously fallen down the stairs after a long bout with the bottle!'

'What do you know! Grapes and gravity make a dangerous combination. We should remember that,' chuckled George. 'In his early days, Newton did his best work not in Cambridge, but outside it.'

'You mean during the two years of 1665 and 1666 when Cambridge was closed because of the plague. *Anni mirabiles*, the Miracle Years of Isaac Newton!'

'Exactly. Maybe it is a good idea to shut down universities for a while from time to time. Some of them permanently perhaps. That way, students will have some time to think calmly.'

'That is what Newton did during those years at his birthplace of Woolsthorpe, didn't he? Think calmly and intensely. You know what he said in his old age about the work he had done during that time? He said:

> *All this was in the two plague years of 1665 and 1666, for in those days I was in the prime of my age for invention, and minded mathematics and philosophy more than at any time since.*'

'Newton's two words '*All this*' contains a staggering amount of work, Alfie. In just two years, he had laid the foundations for his mechanics, optics, calculus or fluxions as he called it, and gravitation.'

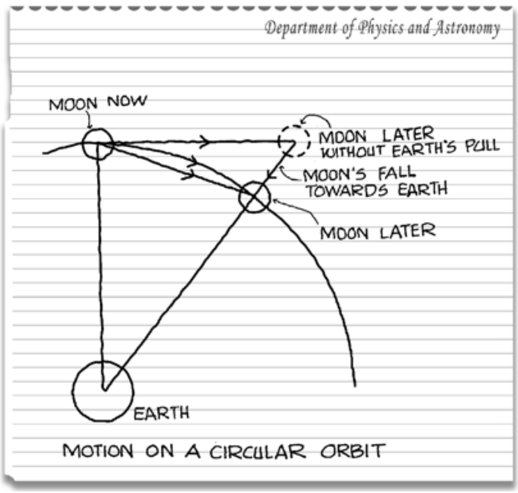
'Gravitation! The fall of the apple. So much has been written about that event by so many people, you know. Voltaire, De Morgan, Brewster and Newton's young friend, Dr. Stukeley, to name but a few. The apple has become the symbol of earthly gravity, hasn't it? A nice metaphor if you ask me.'

'Agreed. But, remember, the law of gravitation did not occur to Newton as a flash of divine inspiration as the apple fell. It is a pity that often people think that is how it happened. He discovered it by comparing the fall of the apple with the fall of the Moon towards the Earth.'

'What do you mean, the fall of the Moon towards the Earth? Even an elementary-school child knows that the Moon is going in a circle around the Earth.'

'True, Alfie, true. But, by falling towards the Earth all the time. If not, the Moon would fly off along a tangent to the circular orbit. Like a stone let go from a sling shot.'

'Like David killing Goliath.'



'Right. But gravity keeps pulling it inwards towards the earth. Compare the position on the tangent where the Moon would have been to where it actually is. Here, give me my writing pad and I'll draw it for you.'

George sketched with his right hand while holding his kielbasa sandwich with the left.

'You can see the Moon has fallen towards the Earth in order to keep to its orbit.'

'Fantastic. How do you compute this fall?'

'By fall you mean the acceleration. Like the acceleration of the falling apple because of gravity, which is known from actual experiments performed on the Earth. The acceleration of an object moving in a curved path like the Moon's orbit is known as its *centripetal acceleration*. The Dutch physicist Christian Huygens had previously shown how to calculate this, and Newton acknowledged that. Well, Newton determined the centripetal acceleration of the Moon from its period of revolution around the Earth and its distance.'

'Then what?'

'Then Newton assumed that the Earth attracted the apple and the Moon with a force which varied as the inverse square of their distances from the centre of the Earth. Namely, the Earth's radius and the radius of the Moon's orbit respectively. So, Newton compared the ratio of the inverse squares of these two distances with the ratio of the corresponding accelerations.'

'And?'

'And they agreed! Let me quote what Newton said years later. I don't have your memory for these things. So I photocopied some quotations to match your repertoire.'

George pulled out a sheaf of papers from his pocket and selected one sheet.

'Here we are. This is from a note Newton wrote years later.

> *I thereby compared the force required to keep the Moon in her orb with the force of gravity at the surface of the earth, and found them answer pretty nearly.'*

'He must have rushed off to publish this fantastic result like Archimedes running out of his bath!'

'No way! That is what we do nowadays, rush to publish even the most trivial things we find out. But Newton kept his discovery aside for nearly twenty years.'

'Twenty years! Why? Because '*answer pretty nearly*' was not good enough for him, or what?'

'That is a mere technicality, Alfie,' said George. 'There was something extraordinary underlying his idea. You see, Newton had used distances from the centre of the Earth for his computations. This meant that the Earth exerted its force of attraction as if its entire mass was concentrated at its centre! Just think for a moment what that means, Alfie. Different chunks of matter distributed at various points within the Earth, considered as a sphere, would be exerting forces differing in both direction and magnitude. When you add them all up, the resultant force should be due to the mass of the sphere acting as if it is concentrated at the centre. This happens to be true only for the inverse square law. Yes, sir, only for the inverse square law! Newton was already on his way to the universal law of gravitation, since he was assuming that every bit of matter in the sphere was separately attracting another object like the apple or the Moon. One step more and he had it. Every particle in the universe attracts every other particle by the inverse square law of gravitation. So Newton must have wanted to prove his assumption first, and then venture to publish his result. And therefore he waited.'

'What happened after those twenty years?'

'Then Halley happened!'

'Ah, I know the story,' I said and repeated what I had read. 'Edmund Halley went to consult Newton on the orbit of some comet. Halley asked Newton what would be the orbit of an object moving under the influence of an inverse square law. Newton readily answered that it would be an ellipse. Halley, completely bowled over on learning how much work Newton had done, persuaded Newton to publish it all in the form of a book.'

'That's right. And Newton worked and wrote like a man possessed and produced the book in just eighteen months! The Book of Books, the *Principia*, was born. And with it a new era in science.'

I saw, at that moment, a young man coming towards us, jogging. Tall, slim and almost boyish, he was smiling broadly at George. When he reached our table, he did not stop but kept jogging, going round and round us in circles.

'Hello George, I have been looking for you all around the campus. What are you doing here, hiding from the rest of the world?' he asked George.

'Not hiding, Mike, since you found me. Alfie here and I were having lunch while discussing Newtonian physics. Alfie, meet Michael Brown, our resident astronomer.'

We said hello to each other.

'Mike, why don't you sit down for heaven's sake?' George remonstrated. 'Going round and round like that is making me dizzy.'

'Never at rest, George, as your old Newton would say.'

'What is that?' George enquired in surprise.

'Never heard what Newton said about correcting one's errors? *He that is able to reason nimbly and judiciously about figure, force and motion is never at rest till he gets over the rub.*

That's me. As for your getting dizzy on account of my circling you, I think it is a good example of Machian effect.'

'What is this Machian effect?' It was my turn to enquire.

'The Austrian physicist Mach conjectured that the inertia of a body is produced by the mass distribution in the rest of the universe,' George explained. 'An offshoot of this is that a rotating body makes other objects turn too. This is the Machian effect Mike is talking about, ridiculous man. We shall get back to this effect when we talk about rotating black holes.'

'George, I almost forgot why I came looking for you,' Mike told George. 'This evening we will be performing Allegri's *Miserere* in the University Chapel. Please do come. That goes for you too, Alfie. See you guys later.' Mike jogged away.

'Wonderful boy,' remarked George following the receding figure of Mike. 'Motivated, bright and talented. One of these days, we'll visit him in the University Observatory. You will get a feel for how they look at the things in the sky. Lunch break is over, Alfie. Turned out to be a working lunch after all, didn't it? Shall we get back to the park?'

We stood up, deposited the used paper plates and cups in the garbage bin nearby, waved to Andy, and made our way back to the University Park.

Chapter 5

COSMIC FRAMEWORK

The park, almost deserted at this hour, was carpeted with dappled shade as sunlight streamed through the leaves of the trees. We sat down on our bench and I placed the big book between us.

'George, before we go deeper into Newtonian physics, I would like to ask you a question,' I said. ' Probably it is only of academic interest.'

'Go ahead.'

'The black hole is purely a product of Einstein's general theory of relativity, am I right?'

'Absolutely.'

'Then why should we learn about Newtonian gravity, however fascinating it might be?'

'A very good question indeed!' George approved. 'Let me explain. First of all, as you yourself pointed out, the black hole is an undisputed offspring of the general theory of relativity. So, in order to study black holes you have to understand general relativity. Do you agree?'

'Agreed.'

'As we shall soon find out, Einstein's general relativity is a geometric theory of gravitation. It is a theory of spacetime, a radical departure from Newtonian gravity. But tell me. Unless we understand Newtonian gravity first and the phenomena it describes, how can we appreciate what happens in Einstein's theory? And also how Einstein differs from Newton? But there are links between the two theories. Some of the Newtonian concepts are taken over into general relativity with suitable modifications. You know, general relativity becomes important and sometimes absolutely indispensable when we deal with strong gravitational fields. As in the case of black holes, for example. But when gravity is weak, general relativity should yield Newtonian results. Far away from a black hole, for instance. So this is often taken as a criterion to check specific results one derives from Einstein's theory. As a matter of fact, we shall see that all this becomes quite important in black hole physics. So, there you are, Alfie. Have I given enough reasons as to why we should study Newton?'

'More than enough, thank you. Let us get on with Newton then.'

'Which means we take a look at the *Principia*. Here is the masterpiece.'

George held up the big volume that had been lying between us on his two palms as though he was making a reverential offering. Bound in leather and printed on thick paper, it had the appearance of a sacred text.

'The greatest scientific book ever written! Don't take my word for it. Many experts say so.' George pulled out the sheaf of papers from his jacket pocket again and quoted. 'Here is what the great mathematician-physicist Pierre Simon Laplace proclaimed:

> *The Principia is pre-eminent above any production of human genius.'*

I quickly thumbed through the book. It was a veritable forest of definitions, propositions, theorems, corollaries, problems, and scholiums. Page after page was covered with complicated geometric figures – lines, triangles, rectangles, polygons, circles, ellipses and other curves. I was reminded of Galileo's famous statement:

> *Philosophy is written in that great book which ever lies before our eyes – I mean the universe – but we cannot understand it if we do not first learn the language and grasp the symbols in which it is written. The book is written in the mathematical language, and the symbols are triangles, circles and other geometrical figures, without whose help it is impossible to comprehend a single word of it; without which one wanders in vain through dark labyrinth.*

George, who was watching me, remarked, 'Rather humbling, isn't it?'

I nodded quietly. And then added, 'It looks like a difficult book to read.'

'That is an understatement, Alfie,' said George. 'Apparently, Newton himself told a friend that – I quote – *to avoid being bated by little smatterers in mathematics he designedly made his Principia abstruse, but yet so as to be understood by able mathematicians.* But even the ablest mathematicians found the *Principia* difficult to understand. Take for instance, De Moivre, who is well known for his theorem even today. He found much of it beyond his comprehension at first reading. You know what he did? He bought a copy which he tore into sheets and carried a few of them in his pocket at a time, so that he could study them whenever he had leisure.'

'Hope it was his own copy, not borrowed from the library. Why is it so difficult?'

'For one thing, it is written in the language of classical geometry, which is tough. Another problem is his so-called secretive style. He skips many steps in his calculations substituting for them instead phrases like '*hence it comes to pass*', '*by like reasoning*', and so on. No referee would allow our papers to be published if we did that!'

'Reminds me of Nietzsche, who said that words should be like mountains. Only those who can scale them must be able to understand what they mean.'

'Exactly. Let us take a closer look at this living scientific monument. We can only have a glimpse of the treasures it contains.'

George opened the book and revealed the title page. The full title of the work stood out boldly at the top: *Philosophiae Naturalis Principia Mathematica*, Mathematical Principles of Natural Philosophy.

As a prologue to the book, there was something I could never have expected, namely an *Ode to Isaac Newton* by, of all people, Edmund Halley! After extolling Newton's achievements in poetic terms, the Ode ended with the tribute to the great man: *Nearer to gods no mortal may approach.*

'Here is what we shall do,' George spoke up. He had been waiting patiently, while I was examining the *Principia*. 'We shall make a quick tour through the *Principia*. It will be essentially a tour through Newtonian gravity.'

'That would be wonderful, George, a conducted tour with you as the guide, no less.'

'Not really. There are better guides than me. Newton himself for one. We shall see what he has to say about his own work and its implications. Then there are those scholars who have studied the *Principia* with great care,' George patted the bunch of sheets with photocopied passages.

'May I keep those sheets at the end of our discussion?' I asked.

'Of course, all yours to keep,' George smiled. 'Let us begin then. At the outset, Newton defines his absolute space and absolute time. We need not go into the details. Absolute space, according to Newton, without reference to anything external, remains the same and immovable. Similarly, absolute time is supposed to flow without relation to anything external.'

'They seem to be very abstract to me, George. Are they used in any way in experiment or theory?'

'Not at all,' George replied. 'As a matter of fact, the whole idea was attacked by Bishop Berkeley since, according to him, absolute space and absolute time seemed to have all the attributes of God. Later on, they were criticised on physical grounds as well.'

'I suppose all this changed with Einstein's theory of relativity,' I said.

'You are right. But let us continue. Now, once again at the beginning, Newton puts forward an idea, which is extremely important. An idea that we take for granted and use routinely. Here, let me show it to you in Newton's own words.'

George pointed to a particular sentence, part of which he had underlined lightly with pencil. Such markings were all over the book. George read my thoughts.

'I know, one should not deface a book,' George said by way of explanation. 'But writings in pencil can be easily erased unlike those made with coloured markers. You should see the rainbow colours some students cover their books with.'

The underlined parts of the sentence read:

> *Wherefore the reader is not to imagine … that I attribute forces, in a true and physical sense, to certain centres (which are only mathematical points), when at any time I happen to speak of centres as attracting, or as endowed with attractive powers.'*

'Forget how huge the celestial bodies like the Sun and the Moon are,' commented George. 'Forget their structures. Assume they are just points. Assume they are characterized by, but not physically endowed with, mass and power of attraction. Then Newton will show you how those objects move. Entirely from his laws of motion and gravitation. This is exactly what we do when we study the motion of any object, from atoms to galaxies. And Newton started it all. Simple but profound.' George seemed to be carried away by these basic ideas that had shaped science for centuries since Newton.

'Alfie, you were asking about the relevance of Newtonian physics to the theory of relativity, weren't you?' George asked.

'That's right.'

'Here is an example. Rather an important one that occurs right at the beginning. Newton discusses the tendency of all matter to remain either at rest or in uniform motion, motion with constant velocity that is.'

'That is inertia, isn't it?'

'Exactly. But there is more. Look at what Newton goes on to say: *But motion and rest, as commonly conceived, are only relatively distinguished; nor are those bodies always truly at rest, which commonly are taken to be so.* In other words, states of rest and uniform motion are relative. This is Newtonian relativity. He knew that you couldn't tell who is at rest and who is moving with constant velocity, by performing any mechanical experiments. We shall see later on how this became the starting point for Einstein's theory of relativity.'

It was astonishing. Here we were, hardly launched upon the *Principia*, but even the preliminary discussions were pregnant with fundamental ideas that also related to relativity theory, no less.

'Let's continue,' George said. 'Newton now states his three laws of motion with the utmost precision. The same laws we have been teaching our students year after year, decade after decade.'

'I remember them well.'

'As you can see, the *Principia* is divided into three Books. And we are now starting on the First Book,' George announced. 'Alfie, prepare yourself for an avalanche of results. Newton considers motion under the inverse square law of attraction. There is an oblique hint that this is gravitation, but the argument for this he reserves for later. He derives Kepler's three laws of planetary motion. Not only that. He goes on to prove the converse as well. If Kepler's laws are valid, the force has to satisfy the inverse square law. Now comes the crucial result for which Newton had waited twenty years. A sphere acts as if its mass is concentrated at its centre. One can never overestimate the importance of this theorem, which has been hailed as the Superb Theorem. Once he had proved the Superb Theorem, then with the help of his laws of motion and the inverse square law, Newton held the entire Solar System in his palm,' George remarked. 'Did he stop there? No!'

'What else did he do?' Like George, I was getting excited too.

'Remember, we are still dealing with the First Book. We know that the Sun is very heavy compared to the planets. We can therefore assume that the Sun is at rest while each planet goes around it. This is known as the one-body problem. Now, if you consider two objects of comparable masses, say the Earth and the Moon, you then have to take into account the motion of both objects. This is the two-body problem. Newton solved this too. Did he stop there?'

'No!' I answered for George.

'Right on. Take then the Earth-Moon system with the Sun interfering in their affairs. This is the three-body problem.'

'As usual, sounds like a human situation to me!'

'Equally or still more complicated. At least the human problem can be solved once in a while. The physical problem cannot be solved exactly at all. But Newton made a good beginning in handling the problem with suitable approximations. Let me add a bit more here. It so happens that in Einstein's general theory of relativity not even the two-body problem can be solved exactly, let alone the three-body problem.' George then went on 'This is more or less the essence of the First Book.' he informed me. 'All in all, it is a magnificent treatise on mechanics as applied to the Solar System, each result a pioneering discovery.'

From what I had heard so far, the First Book by itself was sufficient to establish the *Principia* as a great work. But I knew that there was much more to come. '*Grow old along with me, the best is yet to be*,' as Robert Browning had written.

'Now we come to the Second Book,' George started up after a very brief pause. 'In the First Book, Newton had considered all motion to be taking place in empty space. Now he treats motion in a resisting medium such as air or water. For instance, he considers motion of objects under gravity, including pendulums when there is air resistance. I must add that Newton deals with the flow of fluids as well in his Second Book. In all this he keeps in mind experimental results, his own as well as those of others. All this is typical Newton. But let me tell you two of the astonishing subjects he deals with. First is his mathematical treatment of wave motion.'

'Wave motion, that is rather important in all physics, isn't it?'

'You said it! Newton derives certain fundamental results for the first time, thus leading the way.'

'What is the other subject?'

'Ah, what he does is simply amazing, Alfie. He wants to find out the shape of an object that meets with the least resistance from the medium saying that it '*may be of use in the building of ships*.' We know now that this problem is important in designing aeroplanes too.'

'Which means Newton was far ahead of his time!'

'Very much so! And he proves it again and again. That, Alfie, is the briefest glimpse of the Second Book. We won't go any further into it, not because it is uninteresting or unimportant, but simply because it is not directly relevant to our story of gravitation.'

George sat back totally relaxed and in a mood of serene contemplation. I could feel that something extraordinary was in the offing. After a while, he opened the *Principia* to reveal the first page of the Third Book.

System of the World, the title of the Book was printed in large letters. George read out what Newton had written in the beginning:

> *In the preceding books I have laid down the principles of philosophy; principles not philosophical but mathematical … It remains that, from the same principles, I now demonstrate the frame of the System of the World.*

'That sounds like too fantastic a claim to make,' I remarked.

'With another man, in another book, it could very well have been a resounding hollow boast. But not with Newton,' George averred. 'Those lines always sound to me like – how shall I put it – like the heraldic proclamation of a triumphal march. And what follows is truly magnificent beyond measure.'

'What exactly does Newton mean by the System of the World?'

'Just that. Newton explains practically everything that was known about the heavens at his time. And much more. On what basis? Just his three laws of motion and one law of gravitation. Incredible!'

The Third Book ran to some two hundred and odd pages, which would unravel the clockwork of the cosmos.

'First of all, Newton describes and accounts for the motions of the moons of Jupiter and Saturn and the Earth,' George continued. 'And, of course, of the planets around the Sun. All within the framework of his gravitational theory.'

'That was the central theme of his whole work, I suppose.'

'To begin with, yes. But, now, Newton performs an incredible feat, invading completely uncharted territories. This is exactly according to the guiding principle Newton sets down right in his *Preface*. Let me show it to you.'

George thumbed back to Newton's *Preface*.

> *For the whole burden of philosophy seems to consist in this – from phenomena of motion to investigate the forces of nature, and then from these forces to demonstrate the other phenomena.*

This was a revelation. 'That seems to sum up the entire purpose of science!' I exclaimed.

'How right you are, Alfie!' agreed George. 'So, Newton sets out to demonstrate the other phenomena now. First, Newton thinks of the shape of the Earth. He shows how, because of its rotation, the Earth bulges out a bit at the equator and is flattened a little at the poles. He calculates this distortion, which agrees pretty well with the modern measurements.'

'The Moon and the planets rotate too. They must also be bulged out in the middle.'

'Yes, and Newton considers this too. As a matter of fact, the shape of rotating fluids is a fundamental problem by itself, Alfie. Many mathematicians have worked on it since Newton's time. Incidentally, you know that basically there are two types of black holes, don't you?'

'Non-rotating and rotating ones, am I right?'

'Right. The Schwarzschild and the Kerr black holes, respectively. The former, which is non-rotating, is spherical in shape. But, owing to its rotation, the latter is sort of spheroidal in shape, bulging out at the equator and flattened at the poles. That is in agreement with Newton's work on rotating objects.'

'Let us consider some more earthly phenomena,' George went on. 'First, let us get back to Galileo. You remember his experiment to show that all bodies, whatever their weight, fell with the same acceleration due to gravity?'

'I certainly do. He must have discovered that using his inclined plane, as we discussed earlier.'

'This has come to be known as the Principle of Equivalence. The acceleration is independent of not only the mass of the body, but also of its composition. Newton demonstrated this by using a pendulum consisting of a hollow box suspended by a string. He showed that the period of oscillations was the same no matter what material he filled the box with. He gives the list: gold, silver, lead, glass, sand, common salt, wood, water, wheat! Newton was a consummate experimenter too, you know.'

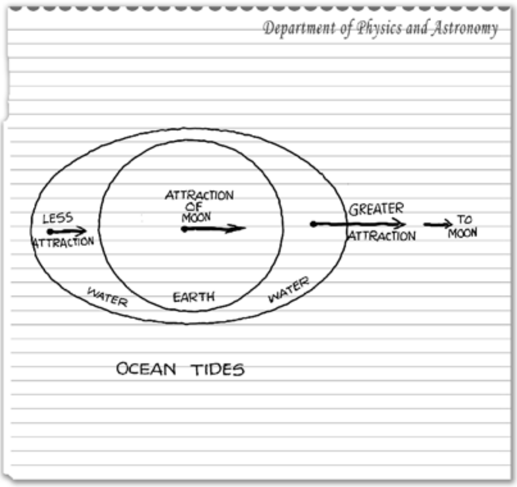
'So, Galileo's inclined plane was replaced by Newton's pendulum then.'

'You are absolutely right. Newton proved the equivalence principle from astronomical observation as well. Later on in the *Principia* this is what he wrote:

> *Bodies projected in our air suffers no resistance but from the air. Withdraw the air and the resistance ceases; for in this void a bit of fine down and a piece of solid gold descend with equal velocity.'*

'Why, that is what the astronauts verified on the moon by dropping a feather and a hammer!'

'Precisely. And here is something extremely important. The equivalence principle was to become the cornerstone of Einstein's general theory of relativity.'



Before I could say anything, George held up his hand in a restraining gesture.

'Hold it, Alfie. I know you are dying to ask me how. We shall have to wait until our next session. The equivalence principle and the birth of general relativity deserve a detailed discussion.'

'All right, master. I shall wait patiently,' I promised.

'Good. Now another phenomenon again of fundamental importance to general relativity, namely the tides or the tidal force. As a fortunate frequenter of beaches, you know all about tides, don't you?

'Yes, I do,' I answered in the affirmative. 'But tell me how Newton explained it.'

'As you know, tides are caused predominantly by the attraction of the Moon and to some extent that of the Sun,' George explained. 'Let us forget the Sun. The gravitational attraction of the Moon varies over the surface of the Earth both in direction and strength, depending on the distance of the relevant point from the Moon. As a result, the Moon's attraction is stronger on the side of the oceans facing it as compared to its force acting at the centre of the Earth. Once again, the force at the centre is higher than that at the side of the oceans facing away from the Moon. Accordingly, the oceans tend to bulge out in the two directions towards and away from the Moon, respectively. Alfie, the difference in the gravitational attraction acting at any two given points is known as the *tidal force*. Newton works out the tidal forces acting on the sea and gives a very detailed account of the tides with facts and figures. Again, we shall see how tidal forces are most fundamental to Einstein's theory. Provided you wait in patience. So you see, Alfie, Newton has so much to do with Einstein.'

'I see it loud and clear, George!'

'Now we fly off from the Earth to the sky once again. You remember how it all began, I mean the writing of the *Principia*?'

'Yes, with Halley's meeting with Newton to consult him about a comet.'

'Right. So, it was but natural for Newton to study the comets. He worked out their orbits and considered the detailed observational data of some of them. In this context he mentions the comet observed by Halley with a period of 575 years – the same comet that had appeared at the time Julius Caesar was killed.'

'I remember what Calpurnia says to Caesar about that comet in Shakespeare's play:

When beggars die there are no comets seen
The heavens themselves blaze forth the death of princes.'

'Well, that used to be one belief, apart from all sorts of other superstitions about comets, Alfie,' George said. 'Newton went on to theorize about the nature of comets and the origin of their tails. He had the rather outlandish idea that some comets may fall into the stars, including the Sun, and fuel them. You remember we talked about the *novae* that were observed by Tycho Brahe and Kepler? Newton conjectures that comets falling into the stars were the cause of those *novae*. But stranger still was Newton's notion that cometary matter, dissipated and scattered throughout the heavens, rejuvenates the Earth and the planets. Whether correct or not, Newton's writings on comets make quite interesting reading, like science fiction, you know.'

George patted the big book with affection. 'Well, Alfie, I think we have had a good glimpse of the *Principia*. What do you say?'

'All that you have told me, that is just a glimpse?' It was unbelievable.

'Yes, it has lot of things we have not discussed. After all, the *Principia* provided the foundation for the work that would be done by great mathematicians like Laplace, Lagrange, Euler and so on. Let me show you what two of them, Laplace and Lagrange, had to say about Newton and his *Principia*. First Laplace: *This admirable work contains the seeds of all the great discoveries that have since been made about the system of the world*.'

'That is a great tribute all right. What did Lagrange have to say?'

'Lagrange expressed his tremendous admiration for Newton, but with a tinge of envy. See, what he says: *Newton was the greatest genius that ever existed, and the most fortunate, for we cannot more than once find the system of the world to establish.*'

'Do you agree with the second part of that statement?'

'Of course not! It seemed so in Lagrange's time. How could he have foreseen that Einstein would do it all over again with his new theory of gravitation? And let us not forget the other worlds revealed by electromagnetism and quantum theory as well as special relativity!'

'*And there are more things in heaven and earth, Horatio, than are dreamt of in your philosophy*,' I quoted from *Hamlet*.

'Precisely, my Prince, at any given time. Now, I just want to read to you parts of the General Scholium, which concludes the Third Book. It is a lofty testament to gravity.'

George opened the *Principia* to the General Scholium. It had been underlined at many places.

'Here are some of Newton's thoughts:

> *Hitherto we have explained the phenomenon of the heavens and our sea by the power of gravity, but have not yet assigned the cause of this power … I have not been able to discover the cause of those properties of gravity from phenomena, and I frame no hypotheses.'*

I had read about this famous last statement: *Hypotheses non fingo!*

'Newton is very emphatic here, as well as in his correspondence, about his firm refusal to hypothesise about final causes. This was a radical departure from the age-old tradition, you understand. In essence, Newton was asserting that he demonstrated *how* gravity worked and not *why*.'

'Isn't that true of all science? You will never reach the final cause, which keeps receding with every step you take forward?'

'You are perfectly right. To continue with the General Scholium, a single sentence summarizes the central theme of Newton's entire work:

> *It is enough that gravity does really exist, and act according to the laws which we have explained, and abundantly serves to account for all the motions of the celestial bodies, and our sea.'*

'That is a superb summing up, George,' I said quite impressed by this statement.

George sat back looking somewhat exhausted. I realized that it was caused not so much by the physical effort required by his exposition as by his passionate involvement with its subject.

'There is one topic we must touch upon without which our discussion of the *Principia* would be incomplete.'

'What might that be?' I was quite eager to know.

'God!' George announced. 'As you know, Newton was a very devout Christian and extolled God and his creation in his General Scholium. Here, let me show you. After describing the Solar System, Newton writes:

> *This most beautiful system of the sun, planets, and comets, could only proceed from the counsel and dominion of an intelligent and powerful Being.'*

'It seems to echo in spirit what Copernicus wrote about placing the Sun at the centre of the planetary system.'

'Yes indeed. Now here is something about God that sounds like an offshoot from his Second Book on motion in a resisting medium. It gives you an impression of almost childlike simplicity.

> *He is omnipresent not virtually but substantially; for virtue cannot subsist without substance. In him are all things contained and moved; yet neither affects other: God suffers nothing from the motion of bodies; bodies find no resistance from the omnipresence of God.'*

'That is quite charming, George!' As George had pointed out, there was childlike innocence in the statement.

'Finally Newton concludes his thoughts about God with his view on the purpose of scientific exploration.

> *And thus much concerning God; to discourse of whom from the appearances of things, does certainly belong to Natural Philosophy.'*

George closed the *Principia* gently.

It was late afternoon. The sun had mellowed and the shadows had started lengthening. George stretched and got up. 'So much for Newton and God. Let us pack up for the day, Alfie. It is time to make our way to the Chapel for the performance of *Miserere* Mike promised us.'

The campus had quieted down. Classes were over. Students had gone home or to the libraries. As we cut across the cluster of buildings, the road narrowed and wound its way among trees and shrubs. The Chapel had been carved out of a large rock that was part of a long craggy ridge. The interior of the chapel resembled a rough primitive cavern. Multicoloured streams of fading light, seeping through stained glass windows with abstract motifs, illuminated the altar at one end. Nowhere was any religious symbol visible. The chapel was dedicated to all religions and no religion. Hardly anyone among the already gathered listeners spoke as we waited in anticipation for the performance of the *Miserere*.

Miserere. The penitential psalm, set to music by the seventeenth century composer Gregorio Allegri, used to be sung in the Sistine Chapel during Holy Week. On account of the *abellimenti*, the skein of delicate vocal lace-work with which the papal choir had invested the plain melodic lines of the chants, the work had long remained a jealously guarded secret. That was until 1840, when, it is said, the fourteen-year-old Mozart wrote it all down from memory after a single hearing.

Miserere. It was one of the same penitential psalms that Galileo had been ordered to recite once every week for three years as part of his punishment.

Have mercy upon me, O God, according to thy loving kindness:
According unto the multitude of thy tender mercies blot out my transgressions.
Wash me thoroughly from mine iniquity, and cleanse me from my sin.
For I acknowledge my transgressions: and my sin is ever before me.

Was this Galileo's just atonement for transgressing the bounds of blind faith and for the sin of questioning authority and bringing truth to light? Galileo's daughter Virginia, who had taken the name Suor Maria Celeste when she became a cloistered nun, had assumed the onus of reciting the psalms on her father's behalf. Lines from T.S. Eliot's *Ash Wednesday* came to my mind, which sounded so apt in this context:

Will the veiled sister pray for
Those who walk in darkness, who chose thee and oppose thee,
Those who are torn on the horn between season and season, time and time,

Between hour and hour, word and word, power and power, those who wait
In darkness? Will the veiled sister pray
For children at the gate
Who will not go away and cannot pray:
Pray for those who chose and oppose
O my people, what have I done unto thee.

Was Galileo one of those who walked in darkness, one who chose but had to oppose? Was he one of those who are forever torn upon the horns of the dilemma between faith and reason? I wondered.

It was almost dark now. The singers, dressed in black robes, walked in single file and took their places. One of them, our friend Mike, caught our eyes and nodded. The performance, as I soon realized, was to be conducted precisely according to the same norms as had been followed centuries earlier. A triangular frame holding fifteen burning candles was brought in and placed in front of the altar. Shadows, in strange shapes and formations, danced on the rough walls of the chapel. The choirmaster, with flowing white hair and a serene countenance, held out his open palms for a moment as if invoking ancient spirits that hovered around, as a solemn hush fell over the listeners, and then he initiated the singing with a slight gesture. I can only describe what followed by borrowing from the letter the composer, Felix Mendelssohn, wrote after hearing the papal choir sing the *Miserere* :

A death-like silence prevails in the whole chapel… And now the Miserere commences, with chord softly breathed out by the voices, causing everyone to feel in his heart the Power of Music. The best voices are reserved for the Miserere, which is sung with the greatest variety of effect, the voices swelling, dying away, and rising from the softest piano to the full strength of the choir. No wonder it excites deep emotion in every listener.

As the singing progressed, the candles on their triangular stand were extinguished one by one. By the time the last canticle was reached, only a single candle remained lit. And at the end, the singers silently marched out, taking away this last flickering taper, leaving the chapel in total darkness, which symbolised a world deprived of the light of Christ. To me it also symbolized the darkness that engulfed Galileo as blindness closed in on him. Slowly the lights came up. And we left the chapel in brooding silence.

Outside, it was a warm night with occasional breaths of a gentle breeze. The tall trees fanned the stars with their swaying foliage. We walked in silence absorbed in our own thoughts.

'You know, Alfie, so much of beautiful art and music has been inspired by devotion to God,' George said after a while.

'From what you have been telling me about Newton, maybe even science could be inspired by religious feelings.'

'Well, perhaps there is a difference. Revelations in science could possibly strengthen religion. And the meaning of religion itself could be open to interpretation. For instance, when Einstein spoke of religion, it had more to do with the awe resulting from the contemplation of nature, a sense of something superior to human beings that underlies the working of nature.'

'But Einstein did not believe in a personal God though.'

'No, Einstein said that he believed in Spinoza's God who manifests himself in the harmony of the universe.'

'I wish God would manifest himself more in the harmony of people.'

'I am sure Einstein would have been in complete agreement with you there. Apart from his great work in physics, Einstein had such profound things to say on so many different subjects. And so beautifully too. But, first we must talk about Einstein's theory of relativity. We shall meet at Bruno's soon and do that. The night is young, but I am old. So I am going home. Take care, Alfie.'

'So long, George. See you soon.'

I too walked home still under the spell of the overpowering music I had heard.

Chapter 6

A MOVING EXPERIENCE

Eyes closed, cradling his face between his palms, Bruno sat back listening to the music wafting in from an old record that was playing in the background. George and I had arrived early to enjoy some quiet moments before the restaurant started filling up. And Bruno had joined us, as he occasionally does, bringing with him a bottle of one of his nameless vintages. Bruno sang along softly with the recorded music. It was a song set to a haunting melody.

Ah, luna della mia notte solitaria!
Per quanto ancora ti nasconderai dietro alle nubi?
Presto la brezza gentile ruberà il tuo velo,
Inondando di luce gli oscuri abissi del mio cuore.
Luna della mia notte solitaria,
Oh, luna della mia lunga notte solitaria!

Bruno opened his eyes slowly and spoke with nostalgia. 'That song I first heard in Napoli. Some traveller translated it into English long time ago. Free translation they say. But he added rhyme so it sounds nice in his language:

Ah, moon of my lonely night!
How long behind a cloud will you hide?
Soon the gentle breeze will draw your veil aside,
Filling the dark depths of my heart with light.
Moon of my lonely night,
Oh, moon of my long, lonely night!

Ah, Napoli, where I spent many years. I can feel it all even now – sunny days, cool nights, beautiful bay, and love everywhere. Sometimes, love brings with it separation and loneliness too, like in the song. You know, a song is the soul of a place, soul of the people.'

Bruno paused recapturing the past. 'We Beltramettis are settled all over Italy, you know. But we come way back from Cremona like our famous relatives, the Beltrami family.'

George sat up with interest, but said nothing. Bruno continued. 'We always looked up to the Beltrami family. They were very artistic. They painted miniatures and engraved precious stones. *Squisito!* But the best of the Beltramis found music more interesting. He was a great mathematician you know.'

George leaned forward. 'You mean Eugenio Beltrami?'

'Yes, Eugenio Beltrami, hero to all of us in our family.'

A couple of people had just walked in. Bruno sighed as he rose. 'I come back to take your orders.' He left our table to look after the new arrivals.

'What was that all about, George? Who was this Beltrami?' I was quite curious.

'Eugenio Beltrami was a renowned mathematician of the nineteenth century, Alfie. Died in 1900,' George replied. 'In those days, mathematicians worked on physics problems too. Like Riemann, Poincaré, and many others. Not like now, when everything has become highly specialized. Beltrami was no exception. He did some first-rate work on the mathematics of curved surfaces, non-Euclidean geometry, electromagnetism and gravitation. All those ingredients that went into the making of Einstein's relativity. In fact, Beltrami even helped in developing some of the mathematical tools Einstein used later on. Beltrami's work might not have influenced Einstein directly. Nonetheless, he represents the general scientific interests of those times. What a strange coincidence, Alfie, Bruno being related to Beltrami!' George shook his head in disbelief.

George sipped his wine with eyes half closed, which meant that his enjoyment was not unmixed with other thoughts. 'You know, Alfie, Beltrami has set a nice mood for our discussion of Einstein's relativity,' George said. 'I am sure you know that there are two theories of relativity.'

'The special theory of relativity and the general theory of relativity,' I answered obediently.

'Let us talk about the special theory, which came first and led to the general theory. Electromagnetism played a crucial role in its formulation. As a matter of fact, Einstein had been fascinated by electromagnetism from an early age.'

'I know. Maybe it was a childhood fixation deeply submerged in Einstein's subconscious.'

'How do you mean? Are you by any chance referring to the young Einstein's magnetic compass?'

'Yes, indeed. I have been reading some books about Einstein and some writings by the man himself too. Absolutely engrossing.'

'And memorizing them all I suppose,' smiled George.

'Absorbing, George, absorbing! Not memorizing. One of Einstein's writings I read was his *Autobiographical Notes*. Quite early in his *Notes* Einstein speaks about the nature of "wonder". This "wondering" seems to occur, he says, when an experience comes into conflict with a world of concepts that is already sufficiently fixed in us. Then he goes on to recount the wonder of such nature he experienced as a child of four or five years old when his father showed him a compass. Einstein says that the needle of the compass behaved in such a determined way! It did not fit into the nature of events at all. Those events could find a place in the unconscious world of concepts based on effects connected only with direct touch. But nobody was holding the needle. This experience apparently made a deep and lasting impression on him.'

'That's right. One would expect that the magnetic needle of the compass could be held in place only by direct touch. Instead, earth's magnetic field was doing the trick. For all we know, Einstein's subconscious, even as a child, was already registering the idea of force fields in contrast to direct touch,' commented George. 'As you must know, Michael Faraday was one of the earliest physicists to think of electric and magnetic fields. At the same time, how simple and skilful were the experiments Faraday performed, Alfie! And from them he showed how electricity and magnetism are intimately related to each other. The two merged into one entity – electromagnetism. This was a fantastic advance, Alfie. No wonder Einstein came to admire Faraday enormously.'

'You know what Einstein said of Faraday: *This man loved mysterious Nature as a lover loves his beloved*.'

'That is probably true of all great scientists, Alfie,' said George. 'Now, another physicist Einstein admired tremendously was James Clerk Maxwell. Maxwell laid the theoretical foundation of electromagnetism. He set down the equations that govern all electromagnetic phenomena. Imagine, that too – just four equations!'

'Exactly like Newton's three laws of motion and one law of gravitation, four in all, that described all celestial phenomena.'

'Precisely, Alfie. Faraday and Maxwell between them laid the foundations of electromagnetism'

'Here we go again. Let me tell you what Einstein writes in his *Autobiographical Notes*, and which is really interesting: *The Faraday-Maxwell pair has a most remarkable inner similarity with the pair Galileo-Newton – the former of each pair grasping the relations intuitively and the second one formulating those relations exactly and applying them quantitatively*.'

'What a wonderful analogy! I envy your photographic memory, Alfie,' George remarked. 'But I do remember Einstein mentioning in his *Notes* that, as a student, he found Maxwell's theory the most fascinating subject. He studied it deeply and it paved the way to his relativity theory. Not the success of the electromagnetic theory but the inconsistencies in its interpretations.'

'How do you mean?' It was my turn to ask George's favourite question.

George smiled. 'You see, the theory, as it was conventionally interpreted, led to a basic asymmetry. Let me explain. You know the famous Faraday experiment. Suppose you have a conducting wire loop. You plunge in a bar magnet into this loop. What happens?'

'An electric current flows in the loop.'

'Now, hold the magnet stationary and pass the loop along the magnet. Then what?'

'Obviously, an electric current flows through the loop as before.'

'Exactly. However, it was argued that, in the first instance, the moving magnet generated an electric field, which was responsible for the current. But in the second case no electric field was supposed to have been created since the magnet was stationary. Instead, it was assumed that an electromotive force was set up in the loop. This force propelled the charges in the loop causing a current to flow. You see, conceptually the two situations were thought to be entirely different.'

'But, George, how is that possible?' I was puzzled. 'The relative motion of the magnet and the loop is the same in both cases.'

'Ah, you have hit the nail right on the head, Alfie, the relative motion!' George nodded approvingly. 'Einstein was deeply perturbed by the inconsistency between the two situations. As you pointed out correctly, they are one and the same if you consider their relative motion. Now do you remember Newtonian relativity we discussed last time, Alfie?' asked George.

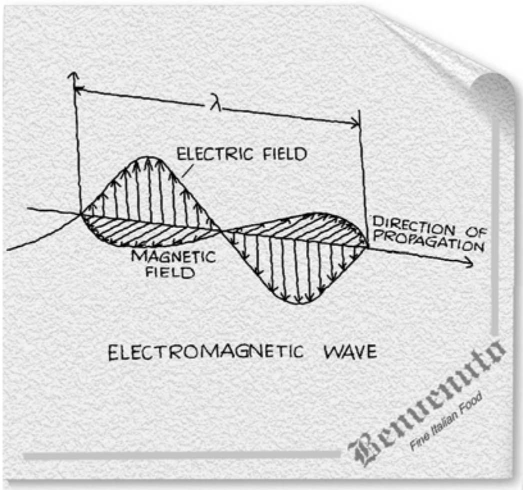
'Sure. If you have two observers moving with constant velocity with respect to each other, you cannot tell by means of mechanical experiments who is at rest and who is moving. Each of the observers thinks that he is at rest and the other is moving. Such motion is only relative. For instance, you can play billiards in the poolroom attached to one of those shady bars in the harbour or on a swanky ship cruising smoothly on the sea, one of those rich affairs you and I cannot afford. You won't notice any difference at all.'

'Excellent. This is known as Galilean relativity also since the idea originated with Galileo, but Newton enunciated it exactly,' George said. 'Einstein felt that this relativity principle should apply to electromagnetic phenomena as well, not just be confined to classical mechanics. So the idea of relativity of all physical phenomena with respect to inertial observers or equivalently inertial frames started taking shape in Einstein's mind. By the way, inertial frames are simply reference frames of observers moving with constant velocities with respect to one another. In these frames, Newton's laws are valid. We now have Einstein's first train of thought that went into the building of his relativity theory.'

'You mean there are more of them?' I enquired.

'Yes, like several streams mingling to make a pool,' answered George. 'Or should we say like rivers creating an ocean? After all, the theory of relativity encompasses all of physics.' George paused, as a good teacher does, before starting off on a new theme. 'Next, we come to a very important electromagnetic phenomenon, that of light. Maxwell's equations describe the propagation of electromagnetic waves. I am sure you know all about these waves.'

'You bet! I deal with them all the time on the project proposals I get. Pity you don't want to hear about those proposals, George. They keep reminding me that these waves range from radio to gamma-rays with visible light lying in between. These waves consist of oscillating electric and magnetic fields. They propagate along wave fronts.'



Following George's example, I sketched the profile of an electromagnetic wave on a napkin as I spoke.

'Good. So the big question was this. What was the medium that supported these oscillations or equivalently the medium through which these waves travelled?' George continued. 'A sensible question since all other types of waves do propagate through some medium or the other, don't they? A ripple expands in water as water particles move up and down rhythmically. Sound waves travel in air as air molecules undergo alternate compressions and rarefactions. So electromagnetic waves needed a medium for their propagation. And this medium was envisaged as the ether.'

'Ah, the mysterious, invisible, jelly-like substance that pervaded all of space and permeated all bodies,' I completed the sentence for George.

'Exactly. Ether was no newcomer to physics, you know,' George commented. 'It was always believed that some kind of elusive substance filled all of space. Maybe physicists, like nature, abhor a vacuum. Newton spoke about ether in his *Principia* long before Maxwell's waves. Newton even tried to measure the resistance offered by the ether to moving bodies with his ever-handy pendulum. That is not all. Would you believe it, he speculated that comets could be concentrations of ether? But this ether remained with no detectable effects and thus elusive for a long time. But now, as the medium for electromagnetic waves, it assumed a reality of its own. As a matter of fact, Einstein too had considered ether as real, and had even thought of experiments to detect it in his youthful days.'

George took a sip of his wine and swirled the glass around as if to simulate the ripples in the ether.

'The ether was considered to be very special,' continued George. 'We were talking about relative motion a while ago. Remember? To paraphrase George Orwell, all motions are relative. But some motions are more relative than the others.'

'Please, George, stop talking in riddles,' I remonstrated.

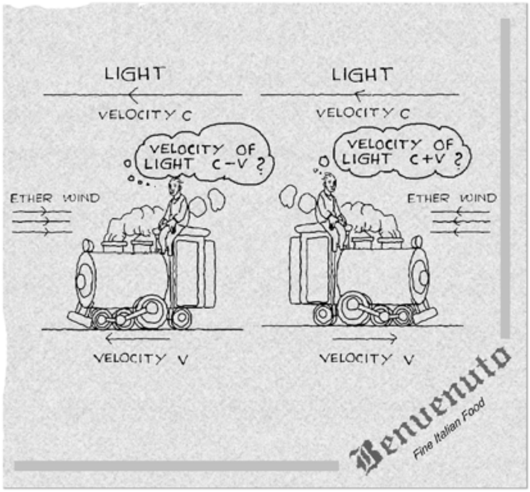
'Oh, I was just following in your footsteps,' George laughed. 'All right, the physicists before Einstein stipulated that all motions had to be ultimately measured with respect to the ether, which defined a sort of global rest frame. Almost like Newton's absolute space. Laws of electrodynamics were considered to be valid only in this frame.'

'Does that mean electromagnetic waves have some special relation to the ether?' I asked.

'The answer is yes,' George nodded. 'They were supposed to move with the constant speed c, amounting to some 300 thousand kilometres per second in a vacuum, relative to the ether. Forget not, relative to the ether.'

'What if you are an observer moving relative to this ether which is considered to be at rest?

'I am sure you have come across that question and the answer to it in your extensive reading,' said George. 'An ether wind would blow against you just like ordinary wind felt in a moving train.



Suppose you consider light travelling in your own direction of motion. The ether wind opposes the motion of this light ray. Then, the speed of light you measure is the speed of light in vacuum measured by a static observer minus the speed of the ether wind, which is the same as your own speed of motion. Likewise, if the light ray travels opposite to your motion, or equivalently along the ether wind, then you would add the two velocities to get that of light as measured by you.'

'So, if you could travel at the speed of light, then the electromagnetic wave should appear to stand still.'

'That follows, yes,' concurred George with a smile, knowing full well, I am sure, what I was going to say next.

'Aha, that is what bothered Einstein for a long time,' I remarked. 'Let me quote Einstein himself on this matter from my data bank. Once again, he writes in his *Autobiographical Notes*:

> *After ten years of reflection, such a principle resulted from a paradox upon which I had already hit at the age of sixteen: If I pursue a beam of light with the velocity of light in a vacuum, I should observe such a beam of light as an electromagnetic field at rest, though spatially oscillating.… From the very beginning it appeared to me intuitively clear that, judged from the standpoint of such an observer, everything would have to happen according to the same laws as for an observer who, relative to earth, was at rest.'*

'That is right,' nodded George. 'Einstein started thinking about this problem as a teenager. Let us talk about the ether wind a bit more. You know about the famous Michelson-Morley experiment?'

'I sure do,' I answered. 'Albert Michelson and Edward Morley tried to detect the ether wind caused by the motion of the Earth by measuring the speed of light in different directions. I remember the boat analogy that illustrates the expected observations. As in the case of a boat on a river, the net speed downstream should be the sum of the two speeds, namely those of light and the Earth, as light is swept along by the ether wind. By the same token, it should be the difference of the two speeds when moving opposite to the ether wind. And the speed is unaffected in the direction normal to the wind. But the experiment failed to show up this difference in the speed of light in different directions. It seems that Michelson was terribly disappointed by this failure to detect the ether wind by his ingenious method.'

'Excellent. There has been some controversy as to whether Einstein knew about this experiment or not. Probably he did,' George said. 'It matters little since he was aiming at finding a fundamental theory.'

'Well, as a matter of fact, Einstein writes that he was looking for a theory of principles, like thermodynamics, applicable to all physical phenomena, and not a constructive theory that just accounted for some observational facts.'

'Such is the theory of relativity, Alfie,' George nodded. 'Let us recap the two major ideas that shaped the theory. You go ahead.'

'First, Einstein wanted electromagnetism to obey the relativity principle. Second, he wanted to set right this business of the ether and the propagation of light,' I said, repeating what I had learnt.

'In a nutshell,' George concurred. 'Achieving these two goals involved intense thought, Alfie. Einstein said that the relentless search generated in him a state of psychic tension, you know. Every serious scientist feels that kind of tension, of course, perhaps on a minor scale. Ultimately, as in the case of all great discoveries, what Einstein needed was a revelation resulting from intuition and creativity.'

'You know George, Einstein has something wonderful to say about these two elements, intuition and creativity,' I recalled. 'Shall I tell you?'

'Of course!' George said emphatically. 'Why do you have to ask?'

'First, according to him, *intuition is nothing but the outcome of earlier intellectual experience*. Second, he characterizes the creative process as *the irrational, the inconsistent, the droll, even the insane, which nature, inexhaustibly operative, implants into the individual seemingly for her own amusement*.'

George reflected for a moment and then observed, 'Alfie, only Einstein could have said that. That man thought so clearly and expressed himself so beautifully. Every statement an aphorism, every utterance a gem. Amazing!'

Let me admit it. Both George and I have tremendous admiration for Einstein. Well, anyone who has studied his work or read his writings would never fail to do so.

'I agree,' I concurred. 'Well, finally we have arrived at the moment of revelation, I suppose.'

'Yes. But more important to us, Alfie, Bruno has arrived to feed us.'

Bruno had indeed come over to take our orders.

'Bruno, I don't know about Alfie here. But I would like to have something simple to eat today,' George announced.

'Same here,' I went along with George.

'How about a salad and good old pizza?' suggested Bruno.

'Ah, pizza, that delectable example of modern Italian cuisine,' exclaimed George.

Bruno looked shocked. 'Modern? Not true! Pizza was born centuries ago in Napoli.'

'I can vouch for that,' I put in.

'How do you know?' enquired George.

'Well, I happened to visit the ruins of Pompeii near Naples sometime ago.' I replied. 'Remember it was destroyed when Vesuvius erupted way back in 79 AD? I was shown, among the well-preserved kitchen utensils, a large circular metal dish that was used for making pizza.'

'I told you, pizza is an ancient dish,' Bruno looked satisfied.

'All right, I stand corrected then,' George admitted a bit sheepishly.

'Bruno, what goes with pizza?' I asked.

'In Napoli people drink only beer with pizza. But I give you some nice Valpolicella,' said Bruno and made his way back to the kitchen.

'Where are we then?' I asked George as soon as Bruno had left. I was quite eager to continue our discussion.

'In space, in the patent office at Berne in Switzerland. In time, the year 1905,' George replied promptly.

'Ah, *Annus Mirabilis*, Einstein's miraculous year in the patent office. Like Newton's two miraculous years in Woolsthorpe. Einstein, holding the exalted position of Technical Expert Third Class, scrutinizes the patent applications diligently in the mornings.'

'And works on his theories in the afternoons wary of the approaching footsteps of his superiors, hiding away his notes if necessary.'

'Discussing physics intensely with Michele Besso, his close friend and colleague in the patent office. And reading books on philosophy that strengthen his abstract thinking.'

'Thinking, thinking. Thinking about the ether among other things.'

'Ether that led a ghostlike existence as Einstein put it.'

'Ether that smacked of an absolute rest frame going against the spirit of relativity. That elusive element, which refused to show up in any experiment. But despair not. Here comes Einstein's first revelation.'

'Namely?'

'That the ether does not exist!'

'Let us drink to that,' I said and we clinked our glasses.

'Maxwell's equations showed that the velocity of light was constant in the ether frame and furthermore that it was independent of the motion of its source,' George continued more seriously after our light-hearted exchange. 'So, if the ether were to be banished, then all inertial frames became equivalent. In this democratic regime, light must travel at the same speed irrespective of the relative velocities of the observers. But, this was absurd, a paradox, according to Einstein.'

'How is that?' I questioned.

'Don't forget Alfie, Einstein still has one foot in Newtonian physics,' emphasized George. 'Yes, built into it is spatial, I don't mean special, relativity. Distances measured by an observer at rest are different from those measured by a moving observer. Of course, motion is relative. We can always choose some observer as being at rest for our convenience. A person sitting quietly by the side of a highway can naturally be considered to be at rest. He sees all the milestones fixed in place. But for the one driving along the highway, the milestones keep coming closer as he moves. In other words, space is relative. Nonetheless, according to Newton all observers in relative motion measure the same time. Or time is absolute.'

'Let me get this straight,' I wanted to make things absolutely clear for myself. 'Time measured by both observers, one at rest and the other moving with constant velocity, is the same. But the distance measured by the moving observer at any given moment is the distance according to the stationary observer minus the distance he has himself travelled in a given time from the start. And this distance travelled is the product of the time interval and the velocity of the moving observer. Am I right?

'Absolutely,' George nodded his approval enthusiastically. 'Do you know what you did just now, Alfie?'

'No, what did I do?'

'What you described to me goes under the name of a Galilean transformation – sometimes known as a Newtonian transformation,' answered George.

'I did?' I was pleasantly surprised. 'What is a Galilean transformation anyway?'

'A Galilean transformation gives the relationship of space and time between stationary and moving observers. As you pointed out, a spatial measurement by the moving observer mixes up the space and time of the non-moving observer. But time is untouched.'

'So?'

'Well, it leads to Einstein's so-called paradox if we consider velocities, even if the ether and the ether wind have been banished from existence,' explained George. 'Let us first take the flight of a bird as an example. The observer at rest traces the distance covered by the bird and divides it by the corresponding time that has elapsed and gets the bird's velocity of flight. Now consider the moving observer. In order to find the velocity of the bird, he divides his own distance measurement by the time interval. And what does he get?'

'He gets the velocity of the bird as measured by the observer at rest minus his own velocity. Come on, George, it is obvious,' I protested. All this was quite elementary.

'Patience, my boy,' George held up a restraining hand. 'What is not obvious, what is taken for granted, is the fact that both observers divided their respective distance measurements by the same time interval. The same absolute time!' stressed George. 'As a result, the velocity of the bird must change from one inertial observer to another. And now we come to the paradox. What is good for the bird is good for light. Therefore, the velocity of light cannot be a universal constant for all inertial observers as demanded by their equal status, unless…' George trailed off deliberately.

'Unless?' I echoed eagerly.

'Unless time itself changes from observer to observer!' declared George triumphantly. 'Here was Einstein's second revelation – his stroke of genius!'

'Let us drink to that,' I said and we clinked glasses again. 'I have read that in his thinking along these lines Einstein was helped by his studying David Hume's philosophical work *Treatise on Human Nature* that considered time in relation to individual perception,' I recounted. 'And it seems a day-long discussion with Besso did the trick in stimulating Einstein's idea of time being relative. Recalling this, later on in life, he is said to have remarked: *It came to me that time was suspect!*'

'Once matters became clear in his mind, Einstein worked out the details of his theory in just six weeks and had it published in *Annalen der Physik*. And, my dear Alfie, here is that paper!'

With a flourish, George took out a book from the large side pocket of his jacket and placed it on the table.

I picked up the book and examined it. Its front cover, distinctive orange in colour, carried two photographs, those of Einstein, which was obvious, and Minkowski, as the caption informed me. I was to learn about the latter's work soon enough. Running to some two-hundred-and-odd pages, this volume, entitled *The Principle of Relativity*, contained several pioneering contributions to the theory of relativity.

George opened the book to reveal the article by Einstein. 'Here it is, the first cannon shot that heralded the relativity revolution,' he announced. 'But look at the title: *On the Electrodynamics of Moving Bodies*. No mention of the word *relativity* at all!'

'Is this a difficult paper to read like Newton's *Principia*?' I wondered aloud.

'Absolutely not. The mathematics is so simple that even a high-school kid can follow it.'

'But not a college student perhaps!'

'Probably not, since the brightest ones may not come to science. But joking apart, the paper is astonishing in its simplicity and direct logic. It should be made required reading for every physicist.'

'So how does it go?'

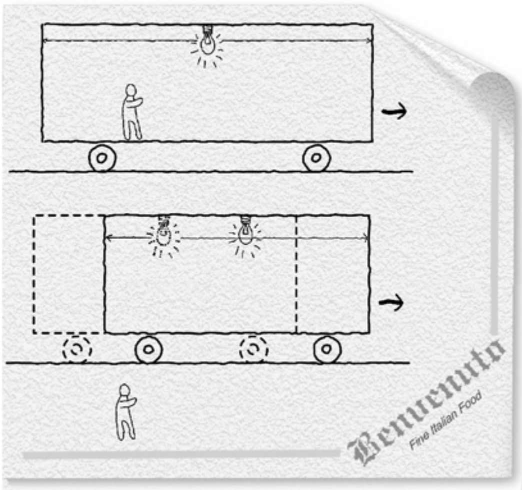
'First, in a brief introduction, Einstein discusses the asymmetry in the interpretation of Faraday's experiment as well as the unsuccessful attempts to detect Earth's motion through the ether. After that, straightaway he sets down the two basic postulates of the theory, namely the relativity of electromagnetic phenomena with respect to inertial observers, and the universal constancy of the velocity of light with respect to all inertial observers. Then with one sentence, one movement, he sweeps away the ether.'

'Just like that?' I was surprised.

'Just like that! Then follows result after result of the relativity theory. To begin with he shows how the notion of simultaneity differs between an observer at rest and a moving observer.'

'That is rather unusual, isn't it?' I asked.

'Most unusual, I must say. It immediately brings in the relativity of time. Let me explain it in simple terms. Not exactly the way Einstein formulated it.' George sketched diagrams to illustrate his explanation. 'Let us assume that a moving railway carriage is equipped with a light bulb right at the middle. Now let it give out a flash of light. If you consider an observer riding inside the carriage, what would he say about the arrival of light at the front and the rear ends of the wagon?'



'Simple. He would say that they arrived simultaneously since the distances travelled by the two pulses are the same for him,' I answered without hesitation.

'Aha, you used the catchword *simultaneously*. Very good. Now what would an observer positioned on the platform say about this business of arrival of the pulses?'

'Well, let me see,' I thought about the situation. 'Let us assume with Einstein that light travels with the same speed for the observer at rest on the platform as for the one travelling along the wagon. Then light would take a longer time to catch up with the front end travelling forward and a shorter time to hit the back, which is rushing towards it. So light hits the two ends at different moments and not simultaneously at all. Incredibly simple and simply incredible!'

'You see, simultaneity becomes relative!' exclaimed George triumphantly. 'The relativity of simultaneity at once shows that time measurement itself has to be relative. What have you got to say?'

'Amazing!' It was indeed.

'Einstein is all warmed up now. Starting from the requirement of universal constancy of the speed of light, he goes on to derive the transformation laws relating space and time as measured by an observer at rest and a moving one, respectively. Remember the Galilean transformations you outlined for me?'

'Spare me my blushes, Watson, as Sherlock Holmes would say.' I felt flattered.

'In those transformations spatial measure was relative. But time was absolute, the same for both observers. Now Einstein shows that time too has to be relative. The new transformations are called Lorentz transformations, named after the great Dutch theorist, Hendrik Antoon Lorentz, who had discovered them before Einstein. So had a couple of other physicists even earlier.'

'So, what was new about Einstein's discovery?'

'Well, his predecessors had no idea of the fundamental, revolutionary principles underlying these transformations. Einstein, on the other hand, had started from the very roots of physics to arrive at these laws. Laws that form the mathematical framework of relativity. Armed with these transformations, Einstein now derives a number of astonishing results.'

'Such as?' I queried.

'First, length contraction. To explain the Michelson-Morley experiment, two physicists, George Francis FitzGerald and Lorentz, had independently postulated that lengths shrink in the direction of motion as measured by an observer at rest. But this was a purely *ad hoc* assumption. But now Einstein actually derived this effect. A stationary observer finds that the length of, say, a moving rod as measured by him is less than its actual value measured at rest.'

'George, you mean to say that if you were to rush fast enough, you would look thinner. You might appear dashing you know.'

'A pun I see. A low form of humour,' George said with a serious face.

'Unintended, believe me.'

'All right. Unfortunately, I wouldn't look slimmer. If you take into account the flight time of light rays from a moving object to the observer, it has been demonstrated that the object would appear rotated and not contracted. Now analogous to length contraction, there is time dilation. According to the observer at rest, the moving observer's clock runs slower than his own. By the way, each observer calls the time measured by him as his *proper time.* Just convenient terminology.'

'Wait a minute. Each of the two observers thinks that he is at rest while the other is moving. Right?'

'Right.'

'Then each of them thinks that the clock of the other is running slow. Not his own. Isn't this paradoxical?'

'No, not really. I would say that there is symmetry between the time measured by the two observers.'

'But I have heard of the twin paradox,' I persisted. 'If one of two twins goes on a space mission and returns home, he would find his earthbound twin grown much older than himself.'

'That is true, Alfie. But the symmetry is broken here. The astronaut twin first accelerates away and then decelerates as he returns to the Earth. He is not an inertial observer at all. A proper analysis taking this fact into account reveals that everything is as it should be. So, no paradox! We shall return to this point when we talk about gravitational time dilation in the framework of the general theory of relativity.'

'I am relieved. Go on then,' I said.

'I don't see what you are relieved about, since you have no twin as far as I know,' George said dryly. 'Using Lorentz transformations, Einstein showed how to compound two velocities. Not just adding or subtracting as in Newtonian physics, but a somewhat different, yet simple operation. Now with his formula Einstein could show that the speed of light would be the same for all inertial observers.'

'That is remarkable. So the paradox related to the velocity of light is completely resolved,' I was getting more and more impressed.

'Right. To continue, after these derivations Einstein addresses the original problem, namely the relativity of electromagnetism. He demonstrates explicitly that Maxwell's equations are invariant under Lorentz transformations. Which means that electromagnetic phenomena would be the same in all inertial frames.'

'Aha, that takes care of the title of Einstein's article,' I commented.

'Correct. Einstein went on to work out some optical effects based on his theory of relativity.'

'All right, what other rabbits jumped out of the relativistic hat?' I asked.

'Relativity of mass! Relativity says that the mass of a particle increases with its velocity,' answered George.

'In other words, if you are running fast, you contract and your mass goes up. But you appear rotated. That is weird. I am not at all sure how you would look like under these circumstances, George, old chap,' I could scarcely hide my grin.

'Would you please spare me all these personal comments,' George protested, feigning annoyance. 'To continue, this increase of mass with velocity was a consequence of the mass-energy equivalence Einstein proved later on. We shall return to this discovery soon. A moving body acquires mass in addition to its intrinsic mass when at rest, or its *rest mass*, by virtue of its kinetic energy. Now, in order to increase its velocity further you have to pump in more and more energy, which again adds to the mass. Finally, you have to expend infinite energy to make the object move at the speed of light, which also means that it would become infinitely heavy. In other words, a material particle will never be able to travel at the speed of light, let alone faster.'

'That means the young Einstein's dream of riding on an electromagnetic wave could never have come true.'

'Alas, such is the fate mortals are subject to, Alfie. That is more or less the gist of Einstein's extraordinary article and some results based on it.'

'And we are told that on All Fools' Day, April 1, 1906, Einstein was promoted to Technical Expert Second Class!'

'Not for his relativity though. A reward for his efficient work on patent applications.'

'How about the celebrated mass-energy equivalence you mentioned a while ago?' I brought up the topic of perennial interest.

'That came two months after his revolutionary relativity paper,' answered George. 'Again it is an extraordinarily simple paper, Alfie. First, Einstein demonstrated the mass-energy relation in the case of electromagnetic radiation. The mass of the emitting system decreased by an amount equal to the energy carried away by the radiation, divided by the square of the speed of light. Later on, by 1907, with his tremendous insight, he had generalized the relation to all possible energies and masses. This was how that ever-famous formula, $E=mc^2$, was born!'

'You know, George, there is record of how Einstein felt when he was thinking of this equivalence,' I said, adding my own bit of information. 'Einstein wrote to Conrad Habicht, one of his old friends, that the argument was amusing and added: *For all I know the Lord might be laughing over it and leading me around by the nose*. What an irony, George! Considering what happened years later in Hiroshima, maybe it was not the Lord at all but His Fallen Angel who was having a laugh.'

'Sadly, yes, Alfie,' George agreed. 'But consider the positive side of the mass-energy equation. It led to the harnessing of nuclear power, explained elementary particle reactions, and unlocked the door to understanding the energy production within the stars.'

George paused for a moment and said, 'I guess we have covered the basics of the special theory of relativity as Einstein formulated it. One more thing to note, which I am sure you know very well. In the same volume of *Annalen der Physik*, at very short intervals, Einstein published two other landmark papers, one on Brownian motion, and the other on the photoelectric effect. The first one established the reality of atoms, while the second one postulated the existence of light quanta. That is what makes 1905 Einstein's *annus mirabilis*.' George sat back as if to take rest for a while, but then leaned forward with pleasure. 'Ah, I see Bruno bringing our salad. A welcome breather before we go on.'

This was a respite that George badly needed and richly deserved. Let me admit it, so did I.

Chapter 7

THE FABRIC OF SPACETIME

Bruno served with pride. We watched with pleasure.

As with every dish Bruno served, the salad was an exquisite artistic creation. A bed of crisp lettuce surrounded the artichoke heart at the centre, crowned with a marinated radish sliced into a red and white flower. It came with a delicately spiced dressing. I am convinced that there must be a direct neural link between the retina and the taste buds. Don't you agree? George and I enjoyed our salad in the comfortable silence that can only be shared between two close friends. After this brief interval, George picked up the threads of relativity once again.

George tapped the orange cover of the monograph lying on the table, indicating the photograph of Minkowski. 'Hermann Minkowski, the brilliant mathematician who was a professor at the Federal Polytechnical Institute, or Poly for short, in Zurich when Einstein was a student there between 1896 and 1900.'

'I know. Minkowski used to complain that Einstein seldom attended his lectures. Apparently Minkowski referred to Einstein as that lazy dog Einstein,' I said.

'The same Minkowski, who had moved to Göttingen by 1905, made a major advance in relativity theory and gave it a beautiful geometric structure. With it, an extremely important chapter opens up in our story.'

George seemed to be turning over a new page in his own mind.

'Minkowski fused space and time and created a new entity, spacetime,' said George. 'This proved to be indispensable to Einstein in his formulation of the general theory of relativity.'

'Let me ask you a silly question,' I interjected. 'Newtonian physics too deals with space and time. Why not have spacetime there too?'

'Not a silly question at all,' George assured me. 'In Newtonian physics, time is the same for all observers. In other words, time stands apart and only the spatial measure changes from observer to observer. So there is no need to combine space and time into spacetime. But in Einstein's theory, space and time are inextricably intermingled. Therefore, you combine space and time into spacetime. Furthermore, different inertial observers measure different things – length contracts, time dilates. You need a common structure shared by all these inertial observers. A house may look different from different angles. But a house has its own identity. Right? And it is the same with the spacetime of relativity shared by all inertial observers.'

'But a house is a house,' I objected. 'You can take its photographs from various sides and from these two-dimensional projections get a fair idea of what the three-dimensional house looks like. But what do you do with spacetime which is four-dimensional, composed of one time dimension and three spatial dimensions?'

'More or less the same thing. Take three- or even two-dimensional projections of spacetime, – mathematically, mind you – and get an idea of the composite structure.'

'Sorry, I don't think I shall ever be able to visualize four-dimensional structures,' I declared.

'For heaven's sake don't even try,' cautioned George. 'You may go raving mad and they might shut you up in an asylum. Come to think of it, it may not be a bad idea after all.'

'You know, when Einstein was working as a professor in Prague, his office overlooked a mental asylum, where its inmates wandered around in the garden. Einstein told one of his visitors that they were the madmen who did not occupy themselves with quantum theory!'

'In your case, on the contrary, you would be the only madcap occupying himself with four-dimensional spacetime, Alfie,' laughed George and added, 'All right, let us first talk about ordinary space and then about spacetime.'

'Suits me.'

'Let us begin with a simple example, the top of this table,' George began. 'It is a two-dimensional space. This pepper pot marks a point in this space. How do I specify its position?'

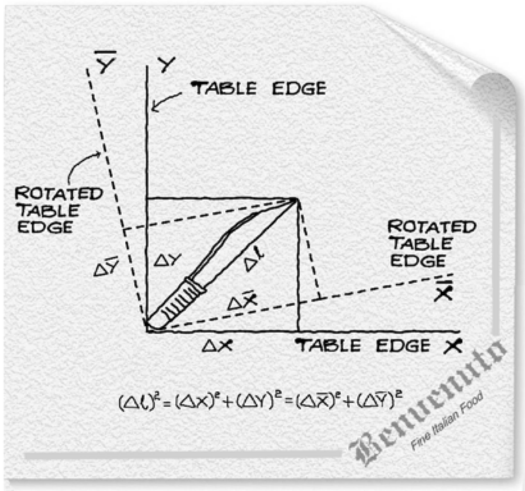
'By telling me its perpendicular distances from the two edges. They are the two coordinates of that point with respect to the edges that act as the coordinate axes. High-school geometry.'

As usual, George sketched helpful illustrations on the paper napkins.

'Alfie, in addition to the diagrams, I shall write down some simple formulae,' said George. 'Often, these formulae and equations require no more than high-school mathematics. But they can tell you much more than just words.'

'I agree, George,' I replied. 'I think the drawings and the formulae together would help a lot. Moreover, they can be a permanent record of our discussions.'

'Excellent. The two edges of the table form a Cartesian reference frame named after its inventor, René Descartes. In a Cartesian reference frame, the axes are always orthogonal to one another,' defined George. 'Accordingly, the coordinates are known as the Cartesian or rectangular coordinates. Call them *x* and *y* for the sake of convenience and convention. Take note of these seemingly trivial facts, Alfie, for we shall be using them later on in more serious contexts. I can fill the top of the table with points and the totality of these points constitute the two dimensional space of the table top.'



'For instance, we could cover the tablecloth with powdered pepper from the shaker to define the two dimensional surface. But then Bruno might throw us out.'

'So we won't do that. Now let us think of lengths. I place my knife thus, with one end at the corner, namely the origin of my reference frame. The projections of the knife along the two edges give the coordinates of the other end. If I add the squares of the projections, what do I get?'

'By George, you get the square of the length of the knife,' I stated the well-known fact. 'Pythagoras told us that centuries ago.'

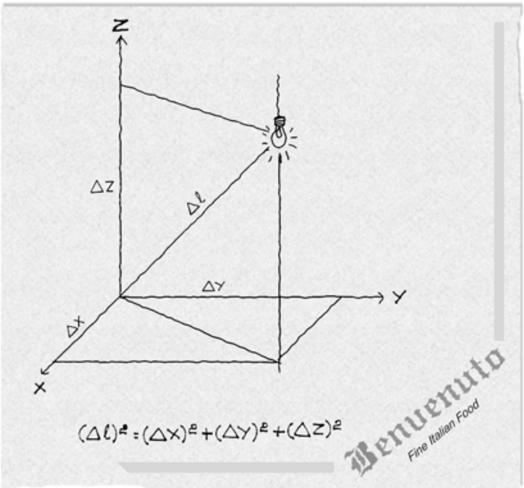
'Good show, except don't swear by my name. Now, suppose I turn just the table, holding the knife by hand in its present position. What happens?'

'The edges, or the coordinate axes, have been rotated and the projections of the knife have changed.'

'Square the new projections or the new coordinates and add. What do you get?'

'The square of the length of the knife as before.'

'So the moral is that coordinate systems can be changed by all sorts of operations – rotate them, move them around, or even invert them by standing upside down and so on,' explained George. 'Coordinates of all the points in space will change then. But the spatial distance between any two points ob-



tained by squaring the coordinate differences, adding them and then taking the square root will remain unaltered. Like the length of the knife. Is that clear?'

'Crystal clear,' I assured George.

'Now all this can easily be extended to three dimensions.'

'I see that,' I volunteered. 'If we take a room as an example of three-dimensional space, we can choose the three edges where two adjacent walls and the floor meet as our Cartesian axes, the corner common to them being the origin. The coordinates x, y and z of a point, say the light bulb hanging from the ceiling, are given by its perpendicular distances from the two walls and the floor. One can find the bulb's distance from the origin by squaring the coordinates, adding them up, and taking the square root. This can be done for any two points to find their mutual separation. How about that?'

'Splendid, Alfie,' George nodded appreciatively. 'What happens if the room were to tilt?'

'Ah, like in Charlie Chaplin's movie *Gold Rush!* Coordinates change, but spatial distances between points remain the same.'

'That is the principle underlying the invariance of spatial lengths.'

'All this is straight forward.'

'But time is of the essence. To unify it with space is our pious wish. Our wish is about to be fulfilled. For, at this moment Hermann Minkowski makes his stage entrance!' George pointed his finger at Minkowski's photograph.

George then opened the orange monograph dramatically, befitting the announced appearance of Minkowski, to his article entitled *Space and Time*. It was a translation of his address delivered at the Assembly of German Natural Scientists and Physicians at Cologne in 1908.

'Let me read the opening lines,' said George.

> *The views of space and time, which I wish to lay before you have sprung from the soil of experimental physics, and therein lies their strength. They are radical.*

'And now for the famous prophetic words of Minkowski,' proclaimed George solemnly.

> *Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality.*

'Aha, Minkowski is about to fuse space and time together into a single entity, spacetime. How does one define it?' I asked eagerly.

'Let Minkowski himself answer your question,' George said and read on.

> *We will try to visualize the state of things by the graphic method. Let x, y, z be rectangular coordinates for space, and let t denote time. The objects of our perception invariably include places and times in combination. Nobody has ever noticed a place except at a time, or a time except at a place. But I still respect the dogma that both space and time have independent significance. A point of space at a point of time, that a system of values x, y, z, t, I will call a world-point. The multiplicity of all thinkable x, y, z, t systems of values we will christen the world.*

'Nowadays, Minkowski's *world-point* is called an *event*,' said George. 'If I clap my hand on my left like this, I have fixed a particular point *where* I clap my hand and a particular moment *when* I clap my hand. The two together define the event. If I clap again on my right, I have another event. The two events are separated both in space and time. If you noticed, I didn't clap my hand loud, otherwise Bruno would have come running.'

'I suppose you can fill all of spacetime or the *world* as Minkowski calls it, with these events,' I continued from where George had left off. 'Let me see. Now time t has also become just a coordinate. In this graphic method, you have three spatial axes for the coordinates x, y, z and another axis to measure time t. Four axes in all, am I right?'

'Right. Again let us see what good old Hermann has to say about this,' answered George.

CHAPTER 7

With this most valiant piece of chalk I might project on the blackboard four world-axes. Since merely one chalky axis, as it is, consists of molecules all a-thrill, and moreover is taking part in the earth's travels in the universe, it already affords us ample scope for abstraction; and somewhat greater abstraction associated with the number four is for the mathematician no infliction.

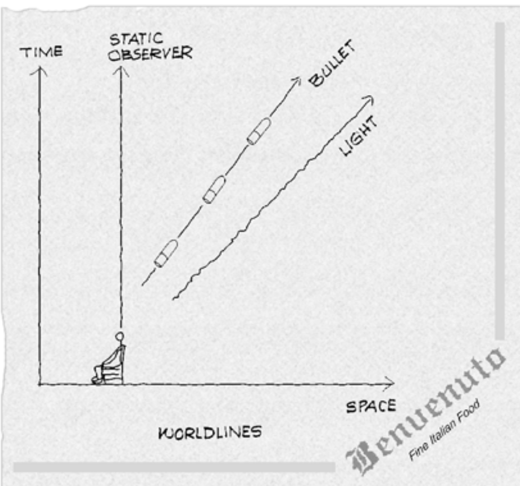
'That is really quaint, George,' I observed happily.

'Isn't it now,' George beamed. 'Normally we represent on paper time *t* along a vertical axis and space by an axis normal to it denoted by *x*. Sometime we fit in two spatial axes, *x* and *y*, normal to the time axis. That is as far as we can go.'

'You leave the fourth axis to the imagination.'

'To mathematics, Alfie, to mathematics and not to imagination! We have to make do with three dimensions to draw spacetime diagrams representing events and phenomena occurring in the four dimensional spacetime. For instance, in the four-dimensional spacetime we have *worldlines.* They depict the history of any object - a particle or an observer.'

'How do you get a world-line?'



'Simple,' replied George. 'You plot the positions of an object as a function of time. For instance, we are sitting here glued to our chairs. We move not, but time passes on. Can you guess how our worldlines look like?'

'Let me think. Simple as you would say. They are straight lines parallel to the time axis, since our spatial coordinates do not change.'

'You got it. How about the world-line of a particle moving with constant velocity, like our inertial observer or a bullet shot from a revolver?'

'The particle covers equal distances in equal intervals of time,' I thought aloud. 'Therefore, George, the worldline is a straight line making an angle with the time axis.'

‘Good. How about light rays?’

‘Well, they also move with constant speed, don’t they? So, they too should be represented by straight lines,’ I answered. After a little thought, I added, ‘We know that the limiting speed of any material particle is that of light. Therefore a light ray should make the maximum angle with the time axis compared to the trajectories of material particles.’

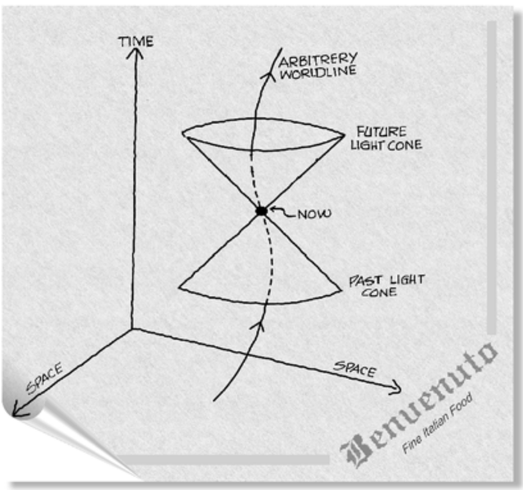
‘Marvellous, Alfie,’ appreciated George. ‘What you just pointed out brings us to the concept of the *light cone*. This concept, introduced by Minkowski himself, has become indispensable for analysing spacetime structure, as we shall find out. Let me now draw some diagrams to illustrate the ideas our pretty little light cone incorporates.’

After a brief pause, George started drawing diagrams, as he explained the light cone.

‘To begin with, let us confine ourselves to only two dimensions. Simplicity always, Alfie. As before, we have now one spatial dimension represented horizontally together with time along the vertical axis. Let us take the origin as corresponding to *now*, the present moment.’

‘How do you fix *now*, George?’

‘That, Alfie, is chosen arbitrarily to suit our convenience. You and I could specify it as the real *now*, this very moment. For a historian, it could be the birth of Christ. An astrophysicist might start reckoning time from the formation of the solar system.’



‘And for a cosmologist, it could be the origin of the universe itself,’ I completed.

‘Right. Suppose you flash a light at the origin. The light pulse travels along a straight path in spacetime defining a ray of light. Let us fix its direction at forty-five degrees to the time axis, again for convenience. So we have two such straight lines each on either side of the time axis. They represent light rays travelling in the opposite directions along the single spatial axis. All trajectories of material particles are confined within this wedge, as you pointed out at the outset. Now, the light pulses travel to the future from the origin, agreed?’

'Agreed.'

'Remember that. Now let us add one more spatial dimension perpendicular to the one we already have. What happens to the wedge?'

'I know. Now you have to represent all the light rays going out in the two spatial dimensions. For this, you simply rotate the wedge about the time axis and the wedge turns into a cone.'

'Brilliant. Now all light rays will have to move along this cone.'

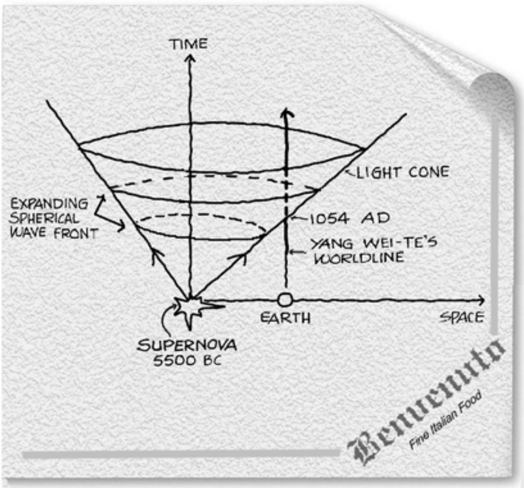
'Obviously it is called the light cone.'

'Exactly. Furthermore light travels into the future and therefore this is called the *future light cone*. Now we can think of light rays reaching the origin from the past. This defines the *past light cone*. Are you with me so far?'

'Absolutely. And all this is very nice indeed!'

'You said it. Let us think of an observer sitting quietly at one spot.'

'His worldline is parallel to the time axis as we saw earlier.'



'Yes. Let us say the future light cone is associated with some event at the origin that sends out light waves. We can select this event to be, say, a supernova explosion. When the world-line of our observer enters the future light cone of the exploded star, only then does the observer see the event. That is when the light from the event, having travelled along the light cone, hits him. Till then he is completely unaware of the event. Think about this on a cosmic scale, Alfie. The galaxies in the sky that we see now, are actually their images as they were millions and billions of years ago.'

'That gives you a strange feeling, doesn't it, George? To think that when you look at the night sky, you are actually getting a glimpse of the history of the entire universe.'

'Of course, Alfie. It is one of those things that inspire awe when you contemplate the cosmos,' agreed George. 'Getting back to the light cone, suppose you flash a light at the origin. Then a pulse of light spreads out in all directions. In other words, a spherical wave front moves out at the speed of light. The spatial cross section of the light cone at each moment tells you where the wave front is at that moment.'

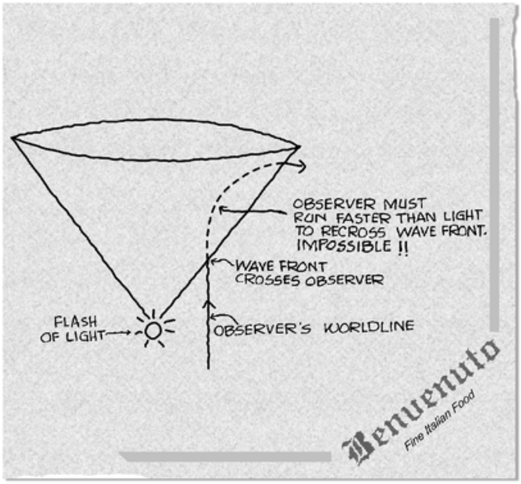
'In our lower-dimensional representation that you have drawn, the wave front looks like a circular ripple ascending along the light cone, doesn't it?'

'Yes, but in the four-dimensional spacetime of relativity, a two-dimensional sphere, the spherical wave front, moves up the two-dimensional periphery of a three-dimensional hyper-cone!' Before I could protest, George added with a grin, 'No, no, I am not trying to make things complicated. Just remember that the light cone represents the evolution of the wave front emanating from the origin.'

'I suppose this is another way of looking at the light cone in terms of the wave fronts, but equivalent to the older picture with light rays.'

'Exactly, Alfie. Let us return to the observer who crosses the light cone at some spacetime point. What does that mean in terms of the wave front?'

'Let me see,' I thought for a moment before answering. 'The light cone traces out the motion of the wave front in time. Therefore, it means that the wave front crosses the observer at that spacetime point as he sits meditating.'



'Very good. This is true of any observer, not necessarily one at rest. Now can the observer re-cross the wave front? Tell me from the physical point of view first,' George told me.

'I suppose not,' I answered readily. 'The observer would have to run faster than light to overtake the wave front which has passed him by. Which Albert absolutely forbids.'

'Now sketch the situation by a spacetime diagram please.'

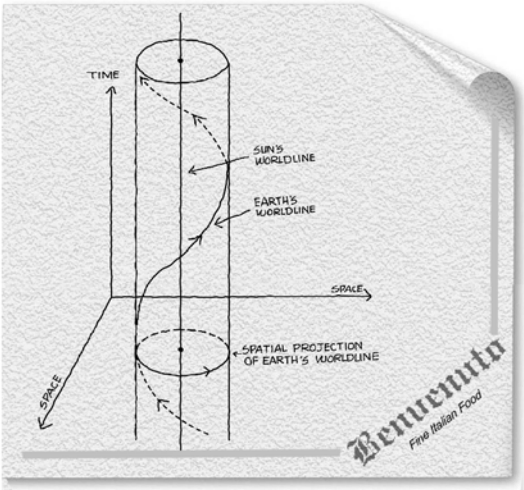
'Slave driver! Let me try,' I remarked and started sketching. 'The worldline of the observer has to bend thus to re-cross the wave front or equivalently the light cone. Aha, at some stage it has to take a path at greater than forty-five degrees to the time axis to accomplish this, which is impossible since that is equivalent to travelling faster than light once again. How do you like that?'

'Amazing. Remember it, store it away in your data bank, and don't lose it.'

'Why, is it so important?' I was a bit puzzled.

'Wait and see, my boy. It is of utmost importance in defining a black hole,' George said with a big smile.

'All right, I shall wait. If the suspense kills me you will have blood on your hands, George, don't forget.'



'Let us get back to drawing worldlines just for fun. A bit more complicated this time. In general, worldlines can follow arbitrary trajectories as long as they are confined to the light cone at every spacetime point along their path, since no material particle can ever travel faster than light. All right, now for a bit of work on your part. Would you mind sketching the worldlines of the Sun and the Earth revolving around it, Alfie?'

'No problem, George. The sun, being static at the spatial origin, describes a worldline that is a straight line along the time axis,' I answered readily and added after a little thought. 'Now let us say the Earth describes a circle around the Sun in the three-dimensional space. But the motion takes place in time. So the circle has to be stretched out in time. Let me draw it. Aha, the worldline of the Earth is a helix coiled around the straight worldline of the Sun as the axis. How about that?'

'Bravo,' George clapped his hands without making a sound. 'Fast work, Alfie, you are catching on. Like this we can represent the motion of all objects by their worldlines in the four-dimensional spacetime. They are frozen histories, curves that thread their way, perhaps from the remote past to the far-off future, passing momentarily through the present.'

I fell silent while George waited, knowing well that I was occupied by some passing thought.

'This concept of a worldline seems to obliterate the passage of time. Rather deceptive,' I remarked. 'It reminds me sadly of what Einstein wrote to Michele Besso's family on the death of his lifelong friend.'

Now he has departed from this strange world a little ahead of me. That signifies nothing. For us believing physicists, the distinction between past, present and future is only a stubbornly persistent illusion.

I wonder whether Einstein had a foreboding of his own death when he wrote that. Einstein followed his friend within a month, you know.'

'Yes, Alfie, time is a strange entity,' George sighed. 'But there is a sort of continuity in time. The past influences the present. And the present determines the future.'

'Ah, that idea was expressed beautifully by T.S. Eliot, George,' I quoted from Eliot's *Four Quartets:*

Time present and time past
Are both perhaps present in time future,
And time future contained in time past.

'Amazing!' George shook his head. 'These poets often know intuitively what we discover with great effort. Yes, past, present, and the future are all connected. And time flows on relentlessly whether we like it or not. We cannot go back to the past. Nor can we jump to the future at will.'

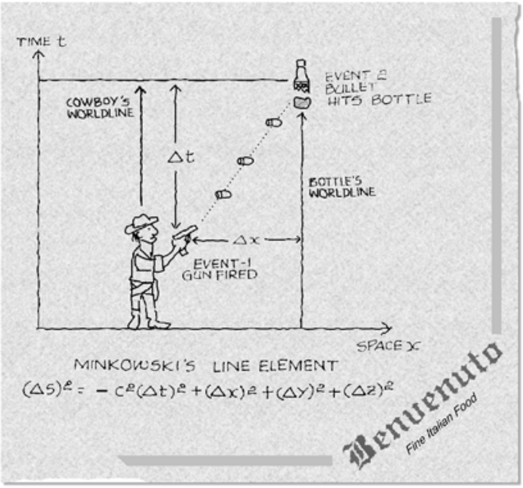
'Then how can you treat time exactly on the same footing as space? We can always return to the spatial point we started from, but not to the same moment in time.'

'Time is not treated *exactly* like space, Alfie. That brings us to the idea of invariant length in spacetime. We saw that spatial length is unaltered under coordinate transformations or equivalent change of reference frames, didn't we?'

'Yes. And the invariant spatial length is obtained from the sum of the squares of the coordinate differences,' I recapitulated.

'And here is Minkowski's brilliant discovery,' George went on. 'First, take the time separation between two events and multiply it by the speed of light *c*. You get a distance in units of spatial length. Let us call this a *time-distance* just like the spatial distance or space-distance for short.'

'Which means one second of time separation corresponds to 300 thousand kilometre time-distance,' I supplied the figure. 'If I am not mistaken, this is



nothing but a light-second, the distance travelled by light in one second. Like the light year.'

'You are absolutely right,' George confirmed. 'Now follow carefully. Take two events in spacetime, square the space-distance between them and then *subtract*, I repeat *subtract* not add, the square of the time-distance between those two events. You see the negative sign in front of the term containing time makes a world of difference between space and time.

That negative sign, a short inconspicuous horizontal line, is time's very own signature. To continue, what you have now is, by definition, the square of the four-dimensional spacetime separation, or the spacetime interval between the two events. This is also called the *line element*.'

'What is so important about this interval?' I asked.

'There lies Minkowski's brilliance,' commented George. 'Minkowski showed that spatial and temporal measurements may change among different inertial observers travelling with different velocities. But the spacetime interval is the same for all of them. In other words, this spacetime interval is invariant under all Lorentz transformations, which take us from one inertial observer to another.'

'I can't imagine the physical and mathematical implications of all this. But I have a feeling that special relativity is built into this invariant spacetime interval since it involves all inertial observers,' I could imagine that much.

'Precisely, Alfie,' George elaborated. 'Once he had hit upon the invariant distance measurement for his four-dimensional spacetime, Minkowski was able to demonstrate how all of special relativity fits snugly into the spacetime cocoon.' George paused and went on. 'Each inertial observer cuts out a different slice of the same spacetime cake. The knife is guided from one slice to another by the Lorentz transformation. When you compare these slices, all the familiar results drop out automatically – length contraction, time dilation, invariance of electrodynamics, the whole works.'

'That is fantastic. You know, George, the spacetime picture is quite appealing even to a layman like me,' I commented after pondering over what George had told me about Minkowski's remarkable work. 'I can very well imagine how elegant it must be mathematically. After achieving all this, did Minkowski continue to work on the theory of relativity?'

'Alas, no,' George shook his head pensively. 'Towards the end of 1908, Minkowski fell ill. He was hospitalised and died of peritonitis in January of 1909. His last words carry a sense of deep regret: *What a pity that I have to die in the age of relativity's development.*'

'How tragic!' I felt really sad.

'Yes, who knows what might have emerged had Minkowski continued to work on relativity,' mused George wistfully, 'or, even better, if he had collaborated with his truant pupil, that lazy dog Albert.'

George heaved a sigh and took a deep breath.

'Well, Minkowski will always be remembered as the Master Weaver who wove space and time together, as weft and warp on his enchanted loom, to create spacetime,' George said. As a distant look came over him, he spoke as if to himself, 'And what a glorious creation it is! The invisible, gossamer fabric of the universe, sprinkled with scintillating events, interwoven with time's delicate threads – the worldlines, and shimmering with myriad, luminous light cones. What a vision!'

After a brief silence, George shook himself from his reverie and exclaimed as he looked around, 'But I see another vision that is both beautiful and bountiful. Blessed are those who behold it and hold it!'

George's face had lit up at this vision as he called it, namely the sight of Bruno approaching our table. Bruno was holding in his gloved hands the circular pan in which our pizza had been baked.

'Watch out, it is pretty hot,' Bruno warned us as he set down the pan on our table. The scarlet tomato sauce, covered with hot bursting bubbles of cheese, sizzled on the freshly baked flaky pizza base.

'Let me tell you, this is genuine *Pizza Napolitana*,' Bruno informed us. 'Recipe comes straight from Napoli, the world capital of pizza. Any *pizzaiolo* in Napoli will tell you that a real pizza is baked only in a *forno*, wooden stove.' And Bruno added with pride, 'We have such a stove you know, brought all the way from Napoli.'

Bruno placed a half-bottle of Valpolicella on the table along with the pizza. Noticing my raised eyebrows, he wagged an admonishing finger at me with a smile.

‘You still have lot to discuss, no?’ Bruno knew by experience. ‘Can’t get tipsy, can we? So only half bottle. Enjoy your meal. *Buon apetito*!’

At that, as if we had heard the pistol shot that starts a race, George and I attacked our pizza with unashamed gusto.

Chapter 8

GRAPPLING WITH GRAVITY

'If music be the food of love, play on', wrote Shakespeare. Did he ever write, 'If music be the love of food, dine on'? If he did not, he ought to have done so, don't you agree? After all, every culinary creation is like a musical composition. It has its own motif, harmony of tastes, orchestration of the constituent elements, and, what is seldom appreciated, its own tempo of presentation. It is a pity that great thinkers, more often than not, have little time to enjoy this fine art, which should be an integral part of everyone's life. Take, for instance, Isaac Newton. Engrossed in his work, many a time he would not even know whether he had eaten or not. Nonetheless, he is supposed to have enjoyed a glass of wine now and then. For, it has been recorded that on some occasions when he entertained friends, he would go to fetch a bottle of wine and, if distracted by some unsolved problem, he would not emerge from his study at all, to the great discomfiture of his guests. And what about Einstein? When questioned about Prohibition, he had remarked, '*I don't drink, so I couldn't care less.*' Einstein disliked alcohol and remained a teetotaller in his later years. He seems to have been not too particular about food either. In 1909, while he was still working in the patent office, the University of Geneva conferred an honorary doctorate on Einstein as part of the 350th anniversary of its founding by Calvin. '*The celebration ended with the most opulent banquet that I have ever attended in all my life*,' recollected Einstein many years later. '*So I said to a German patrician who sat next to me, "Do you know what Calvin would have done if he were still here?" When he said no and asked what I thought, I said, "He would have erected a large pyre and had us all burned because of sinful gluttony." The man uttered not another word!*' Well, there is a day-and-night difference between a glutton and a gourmet. We who enjoy good food and drink follow Epicurus, who advocated moderation. At the same time, we keep in mind the words of wisdom spoken by Shangrila's Chief Lama in James Hilton's *The Lost Horizon*, namely that one should practice even moderation in moderation.

The dishes had been cleared away and the crumbs meticulously swept up, leaving the top of our table a clean surface to work on. Fresh paper napkins had been placed in their holder. George was in a relaxed mood. He had taken off his jacket and draped it around the back of his chair. Food had invigorated him rather than lulling him into torpor.

George sat drumming his fingers on the tabletop, marshalling his thoughts. After a while, he spoke up. 'You know, Alfie, dissatisfaction with the existing order drives some men to great achievements. Often it is true in the case of society and it is true with science. By 1905, Einstein had already made phenomenal discoveries that culminated in the revolutionary special theory of relativity. Don't forget, special relativity itself originated from Einstein's dissatisfaction with the elusive ether and the non-invariance of electromagnetism. Look at the fields to which he had made fantastic contributions, Alfie. Thermodynamics, statistics, quantum theory, and finally the creation of the special theory of relativity! All this was enough to assure him a permanent place among the greatest physicists of all time. But in spite of all these accomplishments we wouldn't have had *the* Einstein we know. What drove him on to the pinnacle of his achievements? Another great dissatisfaction!'

'Why, was Einstein unhappy with his relativity theory?' I was surprised. 'I thought it had succeeded beyond all expectations.'

'Not unhappy, Alfie, but Einstein felt that special theory was wanting on two important counts,' answered George. 'First, the question of gravitation. In Newton's theory, gravitation was a force with instantaneous action at a distance. Wiggle your little toe and the gravitational effect of your action is felt all over the universe at once. Newton himself felt that this was unthinkable. You know, Newton had this perceptive, young theologian friend Richard Bentley, who was deeply interested in the implications of Newton's theories. Newton wrote to him that the action of one body upon another at a distance through a vacuum, without the mediation of anything else, was a great absurdity. That is not all, Alfie. Newton did not consider action at a distance to be instantaneous at all. In a letter to the physicist Robert Boyle, he conjectured that gravitational interaction propagated by means of the condensation and rarefaction of the ether, which acted as the medium. This implied that it took time for the interaction to be transmitted from one point to another. In any event, getting back to Einstein, special relativity had shown that no signal could travel faster than light. So how could any agency transmit gravitational effects instantaneously?'

'Then what was the solution?' I asked.

'No solution, but only vain attempts by a few physicists to fit gravity into the framework of special relativity. It was like trying to fit a square peg into a round hole,' answered George. 'Einstein tried his hand at this game too.'

'And?'

'And he failed,' answered George. 'This made it completely clear, as Einstein himself wrote, that the special theory of relativity was only the first step in a necessary development. To jump ahead in our story, the problem of transmission of gravitational effects was solved only with the advent of general relativity.'

'What was the other shortcoming of the theory?' I asked.

'I wouldn't say a shortcoming, but let us say a constraint,' replied George. 'You see, the special theory was restricted to inertial observers moving with constant relative velocities. There was this Ernst Mach, the physicist whose writings had a profound influence on Einstein, you know. He had earlier questioned the distinguished position the inertial frames seemed to have. Why should they be so unique compared to all other coordinate systems? Einstein wrote that the special theory offered no answer to this question. Besides, we do accelerate all the time and do not just travel with constant velocities, do we?'

'Of course not! Motion with perfect constant velocity is an idealisation, isn't it, George?' I put in. 'Even a train assumed to be in such motion has to accelerate from rest to begin with, and decelerate as it approaches a station. We accelerate at every turn, so to speak.'

'Exactly. So naturally Einstein felt that relativity had to be taken beyond inertial frames, fitting in gravity and acceleration. They are both intimately interrelated, aren't they? After all, you accelerate under the influence of gravity.'

'Ah, I remember. It seems that Einstein remarked that if God had been satisfied with inertial frames, he would not have created gravitation.'

'But how to go about solving this ticklish problem on hand?' George paused. 'Now came the great revelation unto Albert Einstein!'

I remained silent in order not to interrupt George's train of thought.

'But before revealing the revelation, we need to do some ground work,' announced George, his eyes shining. I knew that his unconcealed pleasure stemmed partly from the fact that he was going to keep me in suspense, as he does now and then. I said nothing, as I had no intention of giving him satisfaction on that count.

'Let us go way back to Galileo's demonstration, which he is supposed to have made from the top of the tower of Pisa,' George continued. 'What was the conclusion drawn from that experiment?'

'That all objects, irrespective of their mass, shape, composition and what not, fall exactly with the same acceleration due to gravity.' I repeated the well-known fact.

'Yes, indeed. Now, what on earth might be the reason for this?' asked George rhetorically. 'Well, to begin at the beginning, every object is endowed with, not one but two kinds of mass.'

'Two kinds of mass? The same object? This would qualify as massive double talk, George!' I retorted.

'Honest, I swear,' George held up his hand as if taking an oath. 'Ask Newton if you don't believe me. What does his second law of motion say?'

'Force is mass multiplied by acceleration,' I answered.

'There you are. You got the first kind of mass, the inertial mass,' said George. 'It measures the inertia offered by an object to any force that acts on it. Punch a guy, the more massive he is, the less he budges. But his reaction may be greater than your action, thereby violating Newton's third law of motion. Anyway, remember the force can be of any type – electric, magnetic or gravitational. Now Newton strikes again with his law of gravitation. The force of gravity exerted by one body, say the earth, on another, say an apple, is proportional to …'

'The product of their masses,' I completed George's sentence.

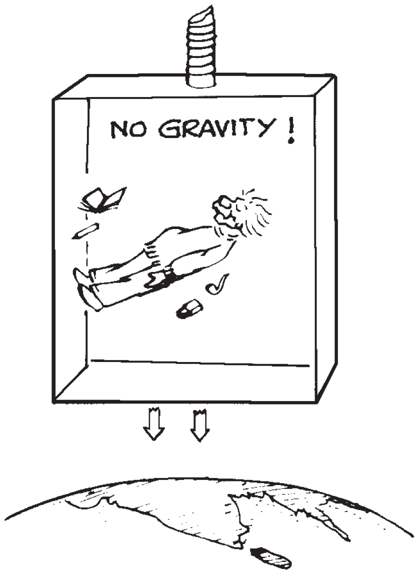
'Aha, now you have the second type of mass, the gravitational mass that enters into this law. *A priori*, the law of gravitation and the law of motion have nothing to do with each other. It is the same with the two kinds of masses involved in these two laws. So, when you stick the gravitational force into the law of motion, you have the gravitational mass of the apple on one side and its inertial mass on the other.'

George paused a moment before stating dramatically, 'But, lo and behold, Nature in her mysterious way, and in her infinite wisdom, has made the two masses equal! So the mass of the apple drops out of the equation. Therefore, Alfie my boy, the gravitational acceleration of each and every object – apple, feather, hammer, or even the Moon – is independent of its mass. All objects fall with the same acceleration.' George continued after a moment. 'The amazing fact is that this happens only for gravitation. If the force is due, say, to an electric field, the acceleration of a charged particle depends on its charge-to-mass ratio. So, all particles won't fall with the same acceleration in an electric field. Einstein realized that this equivalence of gravitational and inertial masses leading to the constancy of gravitational acceleration had profound implications. So, the phenomenon of free fall with the same acceleration for all masses became the key to his new theory of gravitation, or the general theory of relativity as it is called. This was Einstein's great revelation that I mentioned. The revelation has been revealed!' George sat back with satisfaction.

'And you deliberately kept me in suspense!' I said. 'Come to think of it, George, I have come across what Einstein himself recorded about this revelation regarding free fall:

> *When, in 1907, I was working on a comprehensive paper on the special theory of relativity, there occurred to me the happiest thought of my life that, for an observer falling freely from the roof of a house, there exists – at least in his immediate surroundings – no gravitational field.'*

'That is right,' said George. 'When you are falling freely, you do not feel gravity acting on you at all. This process is illustrated by a *gedanken*, or thought, experiment that goes by the name of Einstein's elevator. Cut the cable of an elevator and what do you observe? You are falling freely and so is everything around you. Drop an apple and it will appear suspended in mid-air. If you are standing on bathroom scales, which are also in free fall, they won't register your normal weight, but will show zero. In other words, in a freely falling reference frame such as Einstein's elevator, gravity is annulled.'

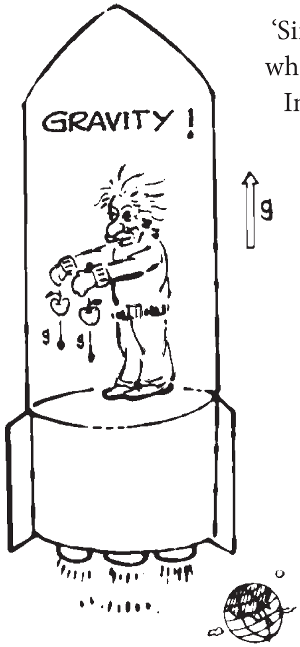


George took out several sheets of paper from his pocket and placed them on the table. He picked out one of them and said, 'Here is a cartoon that depicts the situation.' It showed the Einstein elevator with Einstein floating in air together with several objects such as a book, a pencil, and his pipe.

'Very nice,' I observed, 'But the experiment should remain purely *gedanken* I think.'

'I agree. Having discovered how to annihilate existing gravity, let us see how to create gravity when it does not exist.'

'How?'



'Simple. Let us say we are far away from the earth where, for all practical purposes, there is no gravity. Imagine that we are inside a rocket. Turn on the engines so that the rocket shoots forward with an acceleration exactly equivalent to that experienced on Earth. How would you feel?' asked George.

'Since the floor of the rocket is accelerating upwards, I should feel as though I have my normal weight that I experience on Earth,' I answered.

'You have some imagination there. You are right. Now drop the apple you have stowed away in your spacesuit. What happens?'

'The floor rushes up with the same acceleration as caused by gravity on the Earth. Equivalently, the apple falls to the floor with the same acceleration.'

'Here is another cartoon illustrating this. Now, what is true of the apple is true for all the objects that you may drop. Alfie, do you see what we have done? We have created gravity by going into a suitable accelerated frame, namely the rocket shooting upwards!' exclaimed George with delight.

'Neat. So what?' I asked, rather a bit insolently, I must admit.

'Alfie, to you and me this would have been a mere *so what!* But Einstein's genius turned a simple observation into a great idea,' replied George.

'Ah, Tolstoy wrote in his *War and Peace* that all great ideas are simple!'

'That is true!'

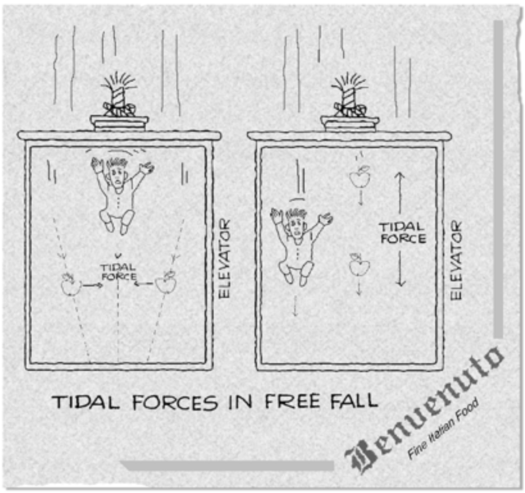
'But fortunately not all simple ideas are great.'

'Thank God for that,' remarked George and continued. 'Einstein realized that a gravitational field could be simulated by a suitable accelerated frame. Now comes his masterstroke. Einstein asserted that whatever you observe in the accelerated frame must happen in the corresponding gravitational field. This should apply to all possible phenomena, I repeat – all possible phenomena – not just mechanical effects like the fall of objects. In other words, the accelerated frame in the absence of gravity is completely equivalent to a static frame of reference in an actual gravitational field. Einstein called this the Principle of Equivalence. That principle turned out to be one of the corner stones of his general theory of relativity.'

'But I have a question,' I said. 'If you can do away with gravity by free fall, then is there absolutely no effect of gravity at all? I mean can you live in the Einstein elevator happily for ever in a gravity-free atmosphere?'

'Excellent question!' said George approvingly. 'As a matter of fact, Einstein himself addressed this question as a footnote in a paper he wrote in 1911. We shall talk about this paper soon. But let me answer your question in some detail. Remember Einstein's happy thought? He is very clear about a freely falling observer not feeling gravity *at least in his immediate surroundings*. Gravity can be considered to be constant over this small region of spacetime. And accordingly, the free fall takes place with constant acceleration only for this small region. Similarly, only a constant gravitational field may be replaced by a uniformly accelerating frame. Such a frame cannot simulate a gravitational field that is varying in space or time. The end result is that you cannot do away with gravity altogether by going to a freely falling frame. Do you follow?'

'Yes and no,' I answered. 'I get the drift of your argument. Can you give me an example? That would help.'



'Certainly,' said George. 'This will take a bit of explaining, Alfie, so bear with me. Suppose the falling elevator was very large, which means you are thinking of a large spatial region. Drop two objects from the same height. They are both attracted towards the centre of the Earth. They would be falling along two different converging paths pointing towards the centre of the Earth. So even if you do not feel they are falling, you will observe them moving towards each other. So gravity betrays its presence in this manner. Then again let us say you have a small elevator but you wait long enough as you fall. Take two objects, one above the other, falling freely with you. The one at a higher level feels less pull of gravity than the lower one. So gradually they move apart as they fall. In both these instances it is the differential gravitational force that is responsible for the relative motion of the freely falling objects. We discussed this differential force earlier, remember?'

'Yes, I do,' I answered. 'When discussing Newton's explanation of the tides. Am I right?'

'Absolutely. It is the tidal force that is showing up here as the essence of gravity that cannot be done away with. What did I say? Newton is still very much with us.'

'Ah, I see his hand all right. As the mathematician Johann Bernoulli said, *we recognize the lion by his paw*! Coming back to Einstein, when did he start thinking about all this?' I asked.

'Around 1907 when he had his happy thought,' replied George. 'He published a paper on relativity that year touching upon gravitation towards the end of the article. After a gap of four years, he returned to the problem of gravitation in 1911. He deduced some novel effects arising from his equivalence principle. He even made concrete predictions that could be experimentally verified. A simple but an amazing piece of work! Here it is.'

The slim volume with the orange cover seemed to be a veritable treasure trove. Einstein's 1911 paper carried the title, *On the Influence of Gravitation on the Propagation of Light*.

'George, this paper contains hardly any mathematics at all!' I was astonished.

'That is the beauty of it, Alfie,' George nodded with enthusiasm. 'It is a simple but profound expression of Einstein's phenomenal insight. Let me briefly outline the results of the paper. Nothing like learning straight from the Master himself! Just to make things simpler, now and then I shall give alternative explanations as well, as I did while discussing simultaneity in special relativity.'

George quickly thumbed through the paper to refresh his memory.

'Right. Einstein first discusses the principle of equivalence. Then he argues how energy increases both inertial and gravitational masses equally, thereby preserving the equivalence principle,' George started off.

'I suppose it was a natural offshoot of his mass-energy equivalence,' I guessed.

'Indeed. Now Einstein is ready to explore some consequences of the equivalence principle related to the propagation of light,' George said. 'Let us get into that rocket racing upwards with uniform acceleration. Naturally, it resembles a constant gravitational field. Of course, Einstein speaks of accelerated reference systems and not rockets. Let us install on the floor an atomic clock, which also emits electromagnetic waves, whose oscillations keep in step with the ticks of the clock.'

'In other words, the frequency of the ticks of the clock and that of the waves are one and the same. Am I right?' I offered.

'Exactly. Now let us install, at the top of the enclosure, a receiver and a clock identical to the one below. You can easily see the following effect. Because of the steady increase in the velocity of the rocket due to its acceleration, wave crests starting from the floor have to travel progressively increasing distances to reach the receding receiver. So the waves are more and more stretched out as they climb up towards the receiver. Therefore the wavelength will be longer when the waves arrive at the receiver, compared to when they were emitted. Or the frequency, which is the reciprocal of the wavelength, will be correspondingly lower. This effect goes under the name of the *redshift*, since red has a longer wavelength than other colours.'

'This is like the redshift that occurs in the case of Doppler effect, isn't it?' I ventured.

'That is a good guess, Alfie,' nodded George. 'Needless to say, you know enough about the Doppler effect. Don't you?'

'Don't I? Allow me to prove it. Police use the Doppler effect to catch speeding automobiles. Doctors use it to follow blood flow, which is nice, because Doppler was a physician in the first place. When a source of sound travels away from you, the pitch of the sound – the frequency – drops down. And when it is moving towards you, the pitch goes up. Of course, the motion is relative, the source could be static with the receiver in motion. The shift in the frequency is directly proportional to the relative velocity between the source and the receiver. For the Doppler effect to be appreciable, this velocity should be comparable to that of sound. Doppler effect can also take place with electromagnetic radiation. The spectrum shifts towards longer or shorter wavelengths depending on whether the source is moving away from you or towards you. How about that? Sorry for the long answer to a short question.'

George was listening patiently and smiling benevolently.

'Not at all, listening to you gives me some respite. Moreover, this way I can decide what I don't have to explain,' assured George. 'Einstein in fact used the idea of the Doppler shift to formulate and calculate the redshift in a uniformly accelerating frame or equivalently in a constant gravitational field. Aren't you happy?'

'Ah, great minds think alike!

'Well, when the source on the floor of the rocket emits radiation, the emitter and the observer would be moving with the same velocity. But by the time the wave reaches the observer the observer would be moving with a higher speed because of the acceleration of the rocket. Therefore, there is a relative recession velocity between the source and the observer at the moment of reception of the radiation as compared at the moment of emission. This results in the Doppler shift towards the longer wavelength of the spectrum. This is the redshift Einstein derives in his 1911 paper. Also, he points out that the result is applicable to any kind of gravitational field, not necessarily a constant one.' After a momentary pause, George added, 'And the redshift in turn leads naturally to time dilation.'

'There is more to the story then?' I asked.

'Yes and it is quite important as you will see,' answered George. 'All right then. Suppose the source on the floor of the rocket emits, say, three wave crests and the clock correspondingly ticks three times. Now a wave train comprising these three crests travels up to the receiver. But it has been stretched out by then. Let us say the wavelength has now been doubled. So the observer's atomic clock registers not three but six ticks as the wave train passes him. What does that mean?'

'I know. It means that the proper times measured by the two observers are different. The clock locked onto the source at the lower level is running slower than the one carried by the observer above. This is your time dilation, isn't it?' I answered. And added, 'The redshift and the time dilation are happening within the rocket accelerating upwards.'

'Good. Now what does the equivalence principle tell you?'

'It tells me that the same thing should happen in an equivalent gravitational field. If I send out electromagnetic waves from the ground, an observer at a height should find the waves redshifted. Further, he will say that my clock is running slower than his,' I answered.

'You got it. These effects are called the *gravitational redshift* and the *gravitational time dilation*. Einstein derived the formula for the redshift using Newtonian gravity and pointed out that this effect could be observed in the solar spectrum.'

After a very short breather, George began again.

'Now let us push on to something very important that Einstein derived once again in his 1911 paper,' said George.

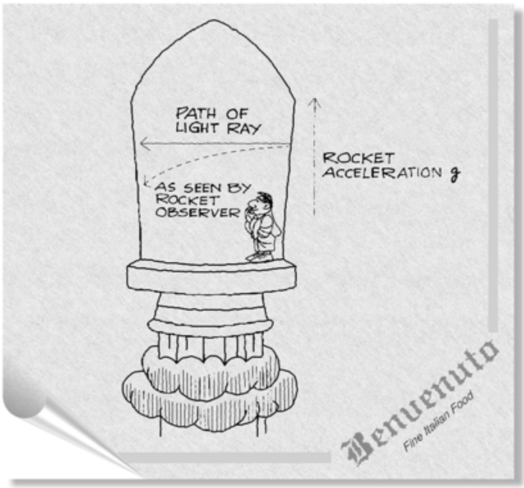
'What might that be?' I queried.

'Gravitational bending of light. Heard of it?'

'Oh yes, I have heard of it. Go on, George, let us have it.'

'Einstein demonstrated this effect by considering the behaviour of light in a gravitational field varying in space. But let me first illustrate it in a somewhat different manner. We'll return to Einstein's method soon enough. Let us get back into our rocket zooming upwards. Now throw a ball horizontally. What would be its path?'

'Let us see. If we could think of a stationary observer outside the rocket, he would see the ball flying along a straight path within the enclosure of the rocket since no force is acting on it. Let us move into the rocket. As the ball tra-



verses its path, the rocket keeps moving upwards accelerating all along. Therefore, for an observer inside the rocket the trajectory must appear curved exactly as in a gravitational field,' I answered.

'Here comes the million-dollar question. Instead of throwing a ball, you send a light ray across the rocket. What then?' asked George leaning forward in anticipation.

'The light ray shoots across the accelerating rocket. The floor of the rocket rushes up with steadily increasing velocity. Therefore, just as in the case of the ball thrown horizontally, the light ray must also appear to bend downwards,' I gave the obvious answer.

'Now invoke the equivalence principle!' George almost commanded me in his excitement.

'A ray of light must bend in a gravitational field!' The conclusion was simple but startling.

'Light bending in a gravitational field! Einstein had discovered a most unexpected effect with far-reaching consequences,' George said with emphasis.

'You mean no one had ever thought of this effect before?' I was intrigued.

George paused before answering. 'Well, to tell you the truth, such a possibility had been speculated upon by none other than ... Guess who?' asked George.

'Don't tell me it was Isaac Newton!' I said incredulously.

'Who else, my dear Alfie, who else?' George exulted. 'Here, let me see, I think I brought the relevant quotation from Newton's *Opticks*.'

I ought to have been surprised by George's forethought, but I was not. He invariably anticipates my questions. George looked through the pile of sheets on the table and brought out a photocopied page.

'This is from the section entitled *Queries* at the end of *Opticks*. Read the very first one of the thirty-one queries he wrote down, Alfie.'

I read out the query at the top of the page. '*Do not bodies act upon light at a distance, and by their action bend its Rays; and is not this action (caeteris paribus) strongest at the least distance?* Amazing, George! This man Newton is incredible.' I remarked. Newton's intuition was indeed astonishing. 'But coming back to Einstein, could he compute the amount of light bending in a gravitational field?'

'Yes, of course,' answered George. 'Einstein considered the fact that clocks run at different rates in a varying gravitational field. This, he argued, meant that the speed of light, as measured with these clocks, also varied correspondingly. The stronger the gravitational field, the lower the speed of light. It is similar to the variation of the speed of light in a medium whose refractive index changes from point to point. This leads to the bending of light as, for instance, in the case of the occurrence of a mirage. So, Einstein concluded that light must bend in a gravitational field as well.'

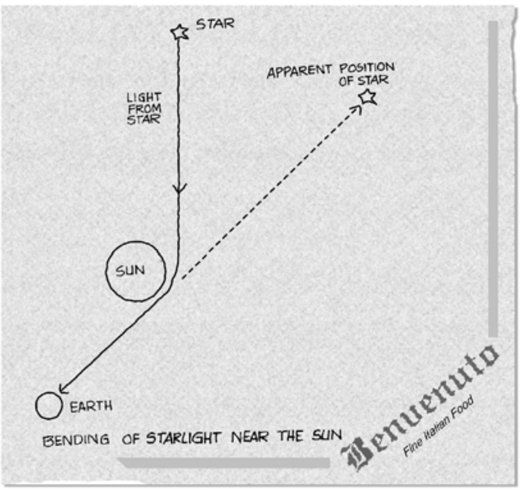
'Wait a minute, George,' I interrupted George. 'I thought velocity of light was a universal constant.'

'That was within the framework of special relativity, Alfie,' George explained. 'Now, with gravitation thrown in, the situation changes. See, what Einstein says: *The principle of the constancy of light holds good according to this theory in a different form from that which usually underlies the ordinary theory of relativity.*'

'What does he mean by that statement?' I asked.

'Well, he doesn't elaborate any further, Alfie,' answered George. 'But we shall soon find out the meaning of this statement when we talk about Einstein's general theory of relativity. It is quite interesting as you will see, and important too.'

'All right, I shall wait patiently as always. Go ahead with the light bending then,' I said.



'Einstein considered the motion of wave fronts as light propagated with varying velocity in a gravitational field,' continued George. 'Using the well-known formalism of conventional optics, Einstein derived the amount of bending. Not only that. As a concrete example, he calculated the deflection of starlight grazing the surface of the Sun. You see, you need strong enough gravitational pull to get an observable amount of bending.'

'And what did he get?'

'He got 0.83 seconds of arc. The actual value should be 0.87, but then arithmetic was not one of Einstein's strong points.'

'But how can you see the stars in sunlight if you were planning to measure the bending?' I wondered.

'Let the old man answer your question,' said George opening the orange book again. 'Here, read what he says at the end of his article'.

I read out the last lines of that wonderful paper.

> *As the fixed stars in the parts of the sky near the Sun are visible during total solar eclipses of the Sun, this consequence of the theory may be compared with experience. It would be most desirable thing if astronomers would take up the question here raised. For apart from any theory there is the question whether it is possible with the equipment present available to detect an influence of gravitational fields on the propagation of light.*

'You see, Einstein was interested in the fundamental question whether gravity has any effect on light at all,' commented George. 'Here is how you go about testing Einstein's result as per his suggestion. At a total solar eclipse, stars become visible. Photograph the apparent positions of the stars appearing near the periphery of the Sun. Compare them with their actual positions. They are obtained from the photographs of the same area of the sky at night taken in the months before or after the eclipse. From this you get the shift in the positions of those stars, which is a measure of the bending of the starlight. It goes without saying that Einstein was quite eager to have his prediction verified.'

'Was it verified then?' This was getting quite interesting, I must say.

'It is a strange story, Alfie,' replied George. 'A German team led by an enthusiastic astronomer, Erwin Finlay-Freundlich, went to the Ukraine in Russia to verify Einstein's prediction during a total solar eclipse. This was in the year 1914.'

'Why, that was the year the First World War broke out!' I exclaimed.

'You've got your history correct all right, Alfie. So the German astronomers were interned by the Russian authorities and they came home empty handed.'

'Einstein must have been terribly disappointed.'

'Naturally. But, you see, when Einstein gave his full theory of general relativity in 1916, he recalculated the bending of light. Guess what he got. *Twice* the value he had obtained in 1911! Imagine what would have happened if Freundlich had found this value and Einstein had given his general theory of relativity afterwards. It would have been as if Einstein had constructed a theory to account for the correct amount by which light was bent. As luck would have it, Freundlich could not measure the deflection of light. Einstein predicted the correct value based on his full-fledged theory. And that was verified in 1919, making giant waves in the scientific world. A very happy ending indeed.'

'That means that Einstein's disappointment was like the one Winston Churchill had experienced when he lost an election. To put it in his own words: *A blessing in disguise, but most effectively disguised at the time!*'

'That describes the situation very well indeed,' said George and sank back in his chair. This meant that we had completed a chapter in the story of Einstein's gravitation.

'George, Alfred Hitchcock once claimed that he made suspense movies, not mystery movies,' I opened our dialogue again after a momentary pause.

'What is the difference?'

'In a mystery you do not know the culprit, and the aim is to find him out from the clues. In a suspense story you already know the culprit, and the excitement centres around the way he is tracked down,' I answered.

'What are you driving at, Alfie?' George frowned.

'Simply this. To Einstein a theory of gravitation was a mystery until he solved the riddle. To us it is a suspense story. We all know the culprit, namely curved spacetime, as every popular book tells you. So far you have not spoken a word about this. Are we getting there?'

'Did you need such a long preamble to ask me such a simple question?' George laughed shaking his head. 'As it happens, Hitchcock is one of my heroes and I agree with his thesis. Now to answer your question. Between what we have learnt so far and the concept of curved spacetime there lies a bridge. The missing link as it has been called, since Einstein never mentioned this aspect in any of his papers on gravitation between 1907 and 1915. This is related to Einstein's study of a rigidly rotating disk.'

'What is new about that?' I asked in surprise. 'Every high school kid knows how it feels to be sitting on a rotating platform or on a merry-go-round and the scientific reason for it.'

'Alfie, every high school kid knows about objects falling down with the same acceleration. What is new about that?' George countered. 'What is important is not the facts we know, but how we look at them. All great scientists – Copernicus, Galileo, Newton, and Einstein – all of them changed our way of thinking by bringing new perspectives to old observations.'

George was absolutely right. What I had read long ago came to my mind. 'George, Marcel Proust expressed the same idea in his own words: *The only real* *voyage of discovery consists not in seeking new landscapes, but in having new eyes.'*

'That is beautifully perceptive and perfectly true, Alfie,' George said with feeling. 'Let us then look at the rotating disk with Einstein's new eyes. We don't have to go into the details of this work, which he did in 1912. Let us just consider the basics. I am certain that you know all about the centrifugal force one experiences on a rotating disk.'

'Sure, George, let me recount what I know. It is actually due to Newton's law of inertia at work, isn't it? When you are going round in a circle, you have a tendency to move off tangentially to the circle at every moment. As a result, you feel pushed outwards. This apparent force is the centrifugal force. Am I right?'

'Perfectly correct,' George agreed. 'You feel as if a force is acting on you because of your inertia, which tries to move you off tangentially as you described. That is why it is called an *inertial force*. At any rate, Einstein pointed out something totally unexpected, which was a consequence of his relativity theory. Suppose you want to measure the circumference of a circle centred round the axis of the rotating disk. It could be the rim of the disk for instance. First, when the disk is not rotating, measure the circumference. What do you get in terms of the radius of the circle?'

'Simple, even the ancient Greeks and Indians knew that. It is twice the product of the number pi and the radius. Do you want to know the value of pi? I can rattle it off to twelve decimal places if you like, 3.141592...'

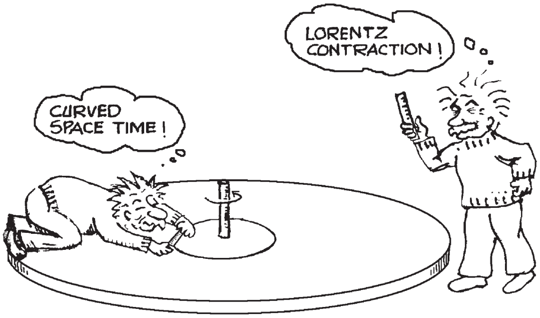
'Hold it for heaven's sake, Alfie,' George held up his hand in mock alarm. 'Now, let us have two observers, a static one outside the disk and the other riding on it holding a ruler, let us call him the disk-man for short. Let the disk rotate uniformly. First let us see what the circle looks like. Our disk-man wants to measure the radius of the circle. So he places the ruler aligned in a radial direction. Does anything happen to the ruler itself as seen by the static observer? Remember your special relativity, Alfie.'

'Well, the ruler is in a direction perpendicular to the motion, which is along the circumference of any circle drawn on the disk about the axis of rotation. So the length of the ruler remains the same as seen by the static man.'

'Good. Therefore the static observer finds the disk-man measuring exactly the same radius as when the disk was not rotating. By symmetry, this is true for all radial directions. In essence, our disk-man concludes that the circle remains a circle with the same radius as before. And the outside observer also agrees that the circle has not changed at all. Now, let the disk-man measure the circumference of the circle.'

'Ah, he places the ruler along the circumference,' I said. 'The ruler is moving with the speed of the disk at that point which is the same all along the circumference of the circle. The man outside of the disk sees the ruler Lorentz contracted.'

'Exactly. The observer outside of the disk finds that his friend on the disk has to place the ruler a greater number of times to cover the circumference than when the disk was not rotating. He attributes this effect simply to the Lorentz contraction of the ruler and is perfectly happy with special relativity at work.'



'All right, so far so good,' I said.

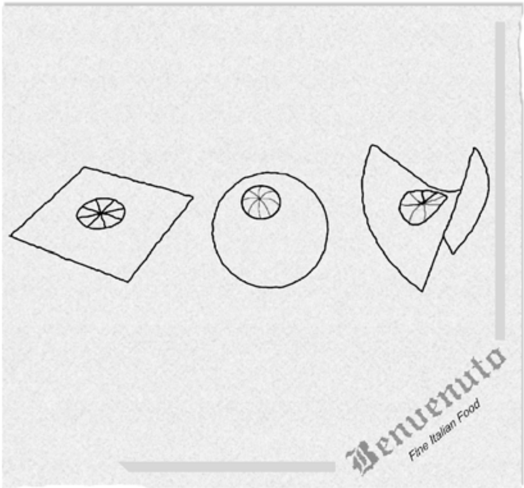
'Now then, let us see what the rotating observer has to say,' George continued. 'First of all, does he see the ruler contracted?'

'No, he doesn't since the ruler is moving along with him.'

'Right. But the number of times he has to place the ruler along the circle will have to be the same as observed by his friend standing outside. This cannot change. Which means the disk-man has to place the ruler a larger number of times along the circumference than when the disk was not rotating. Further, according to him the length of the ruler is the same as when the disk was at rest as he is co-moving with the ruler. Therefore, he measures a higher value for the circumference as compared to when the disk was not rotating. Tell me then, what does this rotating guy find for the ratio of the circumference of the circle to its radius?'

'Greater than twice the value of pi! How can this be?' I was perplexed. 'This goes against everything I learnt about geometry in school.'

'Aha, that is because you never studied the non-Euclidean geometry of curved surfaces in school. Did you?' beamed George. 'Let me give a simple example. Here, let me represent a circle drawn on a flat piece of paper. As you learnt in school when you studied Euclidean geometry, the circumference-to-radius ratio is twice pi. Next, let me show you a circle drawn on a sphere, say for convenience, about the pole. Don't forget, you are totally confined to the surface of the sphere. So the radius you measure is from the pole along a great circle or a line of longitude. You can see that you get a higher value for the radius compared to the circle on a flat sheet. Or equivalently, if you make the radius the same as that of the circle on the flat sheet, you get a lower value for



the circumference. Obviously, the circumference-to-radius ratio will be less than for the flat surface. This is a manifestation of the non-Euclidean geometry of the curved surface of the sphere. Finally, let me draw the surface of a saddle. Dear me, this is a bit difficult. There, I have it. It could be the shape of a saddle-shaped pass between two mountains if you like. This surface is everywhere concave in contrast to a sphere, which is convex all over. The sphere is said to have positive curvature whereas the curvature of the saddle is negative. Just a technical detail. Coming back to the circle drawn on the saddle, for the same radius as before, you get a higher value for the circumference of the circle. In other words, the ratio of the circumference to the radius will be greater than for the flat surface.'

'But that is exactly the result Einstein got for the rotating disk!' This was most intriguing.

'You are absolutely right. So, the spatial geometry of the rotating disk is non-Euclidean, and moreover of negative curvature. I don't mean that rotation warps the disk into a saddle. No, in order to explain the physical measurements and processes on a rotating disk, you have to assume a space with non-Euclidean geometry. Isn't that fantastic? That is not all.'

'There is more? The rotating disk is becoming dizzying!' I exclaimed.

'Oh, yes, it turns you on, doesn't it?' chuckled George. 'Place a clock on the circle. It moves with uniform velocity as the disk rotates. Compare its rate with a clock fixed to the origin, which is therefore at rest. The moving clock obviously runs slower than the one at the origin. You see then that time too is warped. Correspondingly, light from the moving observer gets redshifted when it reaches the observer at the origin. Now, by the equivalence principle, the centrifugal acceleration on the rotating disk is like that of a gravitational field. Unlike the gravity of the Earth, which acts towards the centre, this gravitational field increases away from the centre. At any rate, Einstein came to the conclusion that the spacetime engendered by a rotating disk must have a non-

Euclidean geometry like a curved surface. Later on, Einstein recalled that his study of the rotating disk gave him the decisive idea that the mathematical problem he had at hand was connected to Gauss's theory of surfaces.'

'Carl Friedrich Gauss, hailed as the Prince of Mathematicians, ranked along with Archimedes and Newton for his mathematical prowess!' I had read about Gauss.

'The same Gauss, Alfie. Gauss had done brilliant work on the intrinsic geometry of curved surfaces,' George said. 'Actually, his results anticipated the later development of non-Euclidean geometry, you know. We shall discuss a bit of this novel kind of geometry whenever we need it. But, the long history of non-Euclidean geometry is a fascinating tale in itself. We will need a whole evening or more to discuss it. We shall take it up some other time, Alfie.'

'Oh, that would be grand, George.' I was keen on learning about this branch of mathematics all right.

'So, we have reached a crucial point in our journey. We have arrived at curved spacetime. And Einstein is ready to take off. But we are not, since we need some rest, don't we? '

This was the moment to pause and ponder. I could sense that we were on the verge of important developments. My mind was wandering over all that I had learnt. What was George thinking about? Maybe he was going over what he was going to tell me. Maybe he was not thinking about anything at all. In any event, he looked quite contented.

Chapter 9

BEETLES ON A BRANCH

There was a serene calmness in the atmosphere. The haunting melody of the music playing in the background filled the air. I could not understand the words. That added to the charm of the music, imparting to it a sense of mystery. What did Einstein have to say about the mysterious? *It is the fundamental emotion, which stands at the cradle of true art and true science. He who does not know it and can no longer wonder, no longer feel amazement, is as good as dead, a snuffed-out candle.* How fortunate it was, I thought, that I could feel the mysterious both in the music I was hearing and in the science I was learning.

George soon resumed our discussion.

'So, Alfie, we have arrived at spacetime that is curved,' George began. 'As always, let us start with ordinary two-dimensional surfaces. But before we talk about curved surfaces, let us first think of a flat two-dimensional surface like, for instance, this napkin spread out on the table. Let us identify some characteristics of this flat surface. Then we can see how a curved surface differs from it. Take two neighbouring points on the flat sheet of paper. What is the curve joining the two points that gives the shortest distance between them?'

'Simple enough. It is a straight line of course.'

'Simple enough, Alfie, but underlying it is a very important geometrical concept,' said George. 'On any given surface, take two points. Connect them by all possible curves. Then the one that gives the shortest distance is called the *geodesic* between those two points. On a flat surface, all geodesics are straight lines. Conversely, if the geodesics on a surface are all straight lines, then that surface must be flat. Please store this away in your mind for future use. Now then, construct a triangle using these geodesics, which are straight lines. What is the sum of the interior angles?'

'Simple again. One hundred and eighty degrees.'

'Store that too. Let us get on with the next point. We have already discussed how to determine the distance between two adjacent points using coordinate systems, haven't we?'

'On a flat surface we can use Cartesian or orthogonal coordinates,' I replied.

'Right. And what is more, the flat surface can be covered all over with identical Cartesian coordinate systems. Squaring and adding the coordinate intervals gives the square of the distance,' George recapitulated.

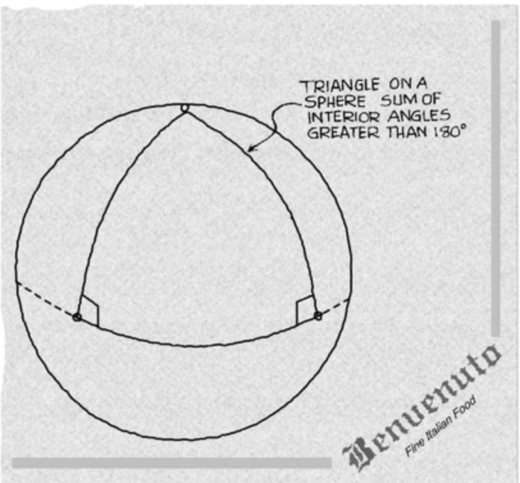
'Good old Pythagoras said so, as we mentioned earlier.'

'True. Now let us move on to a curved surface, say, that of a sphere for instance, and see what happens to the properties of the flat surface,' said George. 'Imagine that we are inextricably confined to this surface. We are like ants crawling on the sphere, blissfully unaware of the third dimension. In other words, we are studying the intrinsic properties of the curved surface. First of all, let us look at the geodesics on the surface.'

'I know. They are great circles on the sphere,' I volunteered the answer. 'Like the lines of longitude and the equator.'

'Geodesics on a curved surface, which are also necessarily curved, are the generalizations of the straight lines on a flat surface. Both give the shortest distance between any two given points,' George said.

'Yes, in a crooked world, the straightest path is also crooked,' I commented.



'That gives you a good excuse to be devious, doesn't it? Of course, in the case of a surface like the sphere one has to be careful. One segment of the geodesic gives the shortest distance between two points. The other segment gives the longest separation. Now construct a triangle using three geodesics, say, two longitudinal lines and the equator. What would be the sum of the interior angles of this triangle?'

'What do you know,' I exclaimed. 'It would be greater than one hundred and eighty degrees.'

'See, by using such criteria you can tell you are on a curved surface without leaving it and viewing it from outside. As I told you a while ago, Gauss did a lot of work on the intrinsic geometry of curved surfaces. His results foreshadowed the advent of non-Euclidean geometry. Amazingly enough, he wondered whether the space we live in deviated from ordinary Euclidean space. Not only that, he wanted to find out by experiment if this was true or not.'

'How could he do that?' This was strange all right.

'Using what we just saw about triangles! He measured the sum of the interior angles of the triangle formed by three mountain peaks.'

'And?'

'The experiment was inconclusive. The observational error involved was far too large.'

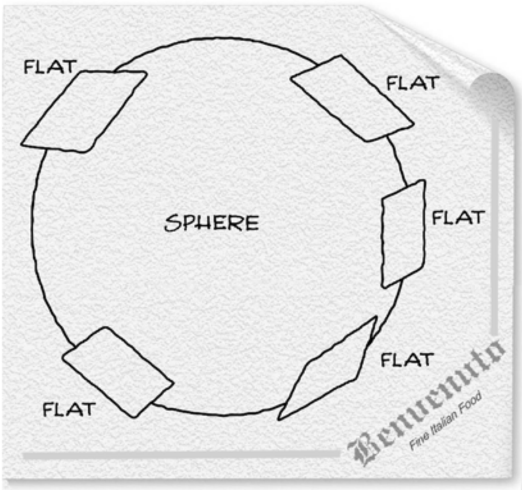
'So Gauss imagined the possibility of a curved physical space long before general relativity then.'

'Well, Alfie, there were other mathematicians who made similar conjectures too. But let us not forget that it was Einstein who showed the reality of a curved spacetime. That was a tremendous achievement, as we are going to see. Let us get back to our two-dimensional surfaces. We spoke about a third characteristic of a flat surface, remember?'

'Oh, yes, the coordinates on the surface. We could cover the flat surface with identical Cartesian coordinate systems entirely.'

'What happens now on a curved surface like a sphere?'

'Ah, on a sphere lines of longitude and latitude form a network to fix the coordinates. One can identify any point this way as on the Earth for instance. But on the other hand, we cannot cover the entire globe with identical Cartesian coordinate systems as on a plane, can we?'



'No, not at all.' agreed George. 'Longitude and latitude circles define a curved system of coordinates. However, at a single point, we can construct a minute area that is flat and tangential to the surface of the sphere. On this teeny-weeny plane I can describe a Cartesian coordinate frame. But if we do this at another point, the new little tangential plane won't be parallel to the old one. Correspondingly, the two coordinate systems at the two different points won't be parallel to each other either.'

'This happens right here on our spherical earth, doesn't it?'

'You are perfectly right,' said George. 'I can happily build my house on a flat plot of land and measure distances using Cartesian coordinates. The same is true of another person ten thousand kilometres away. But his flat plot won't be parallel to mine. But put together all the locally flat plots and you get a sphere. This is true of any curved surface. Again, keep this fact in mind, store it away, we will need it soon.'

'Why, all this seems absurdly simple, George,' I commented. 'I can't see how it can be important.'

'What was that quotation of Tolstoy you told me about, Alfie? *All great ideas are simple!* We shall see how this fact that locally you can have a flat patch on a curved surface becomes important in the hands of Einstein.'

'All right, I shall wait,' I said.

As a matter of fact I did wait while George closed his eyes and sat for a while, apparently reflecting and collecting his thoughts. Presently, he opened his eyes and spoke up.

'Let us say the preliminaries are over at least for the time being, Alfie. Now let us get back to Einstein,' resumed George. 'Where were we when we last saw him? Yes, the old man was taking a ride on a merry-go-round or more prosaically a rotating disk. Einstein had concluded that when gravitation was present, spacetime was endowed with non-Euclidean geometry as on a curved surface. Spacetime of four dimensions no less. So to build a theory of gravitation, he would have to generalize the geometry of two-dimensional curved surfaces to four dimensions. For this he needed, first of all, Minkowski's spacetime approach to relativity. This was rather ironical, you know. Because Einstein had been far from enthusiastic about Minkowski's knitting space and time together.'

'I happen to know that, George,' I put in. 'There is a short but lovely tribute written on Einstein's seventieth birthday by his physicist friend Arnold Sommerfeld, which appears in the same volume as Einstein's *Autobiographical notes*,' I recalled. 'In that essay, Sommerfeld mentions Einstein's reaction to Minkowski's unification of space and time: *Since the mathematicians have invaded the theory of relativity*, *I do not understand it myself any more*!'

'That is typical Einstein for you,' laughed George. 'But now he came to realize how indispensable Minkowski's scheme was. Following Einstein, let us focus on four-dimensional spacetime.'

'Finally! Mystery turns into suspense as Hitchcock would have observed,' I commented with relish.

'Well, I am glad you are satisfied at last, Alfie,' remarked George. 'You remember the spacetime of special relativity we talked about?'

'Certainly, every bit of what you told me,' I assured George.

'Well then, that spacetime is shared by inertial observers,' recalled George. 'In that spacetime there is no gravity acting, so these observers are not accelerated. Let us take particles that are not acted upon by any force at all. Then they too move with constant velocities. This is the natural motion inherent to the spacetime of special relativity. What kind of trajectories do these particles describe in the four-dimensional spacetime then?'

'Straight lines as we saw when we talked about worldlines,' I replied readily.

'Straight lines, indeed,' George repeated for emphasis. 'And, here is something very important. One can show that in the four-dimensional spacetime, they are geodesics too! We saw that if the geodesics of a two-dimensional surface are straight lines then that surface itself is flat. Now, how would you characterize a four-dimensional spacetime that has straight lines as its geodesics?' The question was almost rhetorical.

'A flat four-dimensional spacetime of course!' I responded.

'So you see, the spacetime of special relativity is flat. It is called the Minkowskian spacetime after its creator. As we have seen already, one can fill this spacetime with identical Cartesian coordinate frames. Now, square and add the spatial coordinate separations and subtract the square of the time-distance. As I mentioned earlier, this quantity is known as the line element. It is convenient to use the line element for all mathematical purposes. However, its square root gives you the spacetime interval between two events. All this is in conformity with the analogy of a flat two-dimensional surface.'

George held up his hand, his index finger upright, to drive home an important point. 'Now comes Einstein's dazzling flash of insight. Introduce gravitation into the spacetime. Consider the worldliness of particles falling freely under gravity, the most natural motion inherent to this spacetime. And take a look at the light rays as well travelling in four dimensions. How do they all look like?'

'Curved, of course.'

'Einstein now made what he called his *geodesic hypothesis*. He asserted, insisted, demanded, that the curved worldlines of particles and light moving under gravity be the geodesics of the spacetime. Geodesics that are curved!' George was exuberant. 'What kind of spacetime do we have then?'

'A curved spacetime!' I answered, echoing George's excitement, which was infectious.

'There you are, gravitation curves the spacetime,' said George with obvious satisfaction and slumped in his chair as though he was drained out.

After a very brief pause he began again. 'Let me sum up. In the Newtonian theory, gravity was a force. Now Einstein had identified it with spacetime curvature. All particles move along geodesics imbedded in this curved spacetime. Therefore they too have to be curved. In the flat spacetime of special relativity straight paths were the natural trajectories of free particles. Now, when we have gravitation, the natural motion of particles is along geodesics that are curved. This was a remarkable discovery.'

'George, let me tell you something I read which is most relevant to what you have told me. In 1922 Einstein's son Eduard asked Einstein why he was so famous,' I remembered what I had come across.

'And what did Einstein have to say?' asked George with great interest.

'Einstein's answer to his son was this:

> *When a blind beetle crawls over the surface of a curved branch, it doesn't notice that the track it has covered is indeed curved. I was lucky enough to notice what the beetle didn't!'*

'I told you Alfie. Only Einstein could have put it like that,' George said happily. 'Gravity, we certainly feel. But we do not know that it curves the spacetime around us. And no one had noticed that the tracks we cover in this four-dimensional spacetime, the most natural tracks, namely the geodesics, are curved too. What a fantastic imagery!'

I felt as though I was witnessing a grand structure being built up brick by brick. It seems whenever Gauss, whose work on curved surfaces we had touched upon, published a piece of work, he made it so perfect that no trace of his labour remained. He had remarked: *A cathedral is not a cathedral till the last scaffold was down and out of sight.* But here was a process in progress, which was just the opposite of Gauss's ideal. And to follow it step by step was a joyful experience indeed.

'Einstein was now convinced that curved spacetime would form the foundation of his gravitational theory,' George was back on the trail of his story. 'But he badly needed the right mathematical tools to build up his theory of gravitation or the general theory of relativity upon this foundation. Look at the irony again, Alfie. In his school days at the Polytechnical Institute in Zurich, he cut Minkowski's classes and shunned mathematics in favour of physics. Good for him! Otherwise he might have been mired in mathematical details. He might never have developed his physical insight to the degree that enabled him to make so many groundbreaking discoveries. But now he needed mathematics. Fortunately, in 1912 he was back in the Poly as professor of theoretical physics. Then again, his old classmate Marcel Grossman was also in the Poly as professor of mathematics. Now, Einstein turned to him for help.'

'Marcel Grossman whose father had helped Einstein get a job at the patent office?'

'The very same Grossman,' affirmed George. 'And he knew exactly what Einstein needed, namely Riemannian geometry.'

'Is this geometry related to Gauss's theory of curved surfaces?' I asked.

'Very much so. Gauss had initiated the branch of mathematics called *differential geometry*. It deals with curves and curved surfaces in an analytical manner. Bernhard Riemann made a remarkable job of generalizing the formalism in a systematic way to spaces of arbitrary dimensions. Brilliant mathematicians like Gregorio Ricci and Tullio Levi-Civita developed it further. Other mathematicians like our friend Bruno's relative Beltrami made their contributions too.'

'Which meant Einstein had the tools ready to handle his four-dimensional spacetime curved by gravitation,' I added.

'Sure, he had the proper tools he needed. He had the right idea that gravitation meant curved spacetime. But how could he create his theory from this starting point? Ah, that was a monumental task indeed.'

George regarded me, rubbing his chin thoughtfully, as he often did.

'Alfie, I don't want to weigh you down with technicalities,' said George. 'On the other hand I don't want just to talk in the air. So let me give you some idea of the ingredients that went into Einstein's theory in a little bit of detail. Are you game for it?'

'Of course, I am ready as ever, since you are the one doing all the explanations,' I answered.

'Let us get back to special theory of relativity for a moment,' George began slowly to make sure that I understood everything. 'It was confined to inertial frames moving with constant relative velocities. Before Einstein came on the scene, there were, as we saw, these Galilean transformations that took you from one inertial frame to another. Spatial measurements varied from observer to observer. But time was the same. Under these Galilean transformations, the laws of mechanics remained unaltered, or invariant, with respect to all observers in relative uniform motion. This meant that the equations that spelt out those laws had the same form in all inertial frames. Now with special relativity came the Lorentz transformations. Both space and time became relative for different inertial observers. This ensured the invariance of all physical laws, including electromagnetism, as one went from one frame to the other. But, now we have gone beyond inertial frames, haven't we?'

'Oh, yes, we are now dealing with accelerated frames which correspond to different types of gravitational fields,' I responded.

'Exactly. Now, we have what are called *general transformations* rather than Lorentz transformations. For instance, one can go from a static observer's frame to that of an observer on a rotating disk by suitable coordinate transformations. Built into this are the centrifugal acceleration and the consequent physical effects. And, according to the equivalence principle, the centrifugal force simulates a particular type of gravitational field. Here we have an example of transformation of coordinates that take us from no gravity to a specific type of gravity. Likewise, by general coordinate transformations, one can go from one arbitrary accelerating frame to another. Let me mention a very important frame of reference. It is that of a freely falling observer in a gravitational field. So Einstein demanded invariance of physical laws under any general transformation that took you from one accelerated frame to another. In other words, he said that the equations corresponding to these laws must have the same form under these general transformations. Do you follow, Alfie?'

'I do get the idea, George,' I confirmed. 'How did he achieve this invariance?'

'Well, this could be accomplished by writing down all the equations that spell out the laws of physics in terms of mathematical entities called *tensors*. Have you heard of them?'

'Yes, I have, as it so happens,' I answered in the affirmative. 'Let me tell you what I know. We are all familiar with vectors. They have both magnitude and direction. Such as electric and magnetic fields, velocity, force, and so on. Tensors are generalizations of vectors. More complicated but similar mathematical animals. That is just about what I know about these things, George.'

'Good enough, Alfie,' assured George. 'The branch of mathematics dealing with tensors is known as *tensor analysis*. And it was a well-developed field.'

'Ah, I remember something interesting about this field of mathematics,' I interjected.

'What is that?' George asked with curiosity.

'Well, it seems a gifted high-school teacher by the name of Hermann Grassmann made significant contributions to tensor analysis. As no one paid any attention to his work, he wanted to move far away from mathematics. He ended up making outstanding contributions to Sanskrit language and literature!'

'What do you know. Mathematics' loss was Sanskrit's gain,' commented George. 'Now, getting back to general relativity, if you write down your equations in terms of these tensors, then laws of physics automatically remain invariant when you go over from one accelerated frame to another. The equations have the same form. Of course, when you work out the details using particular coordinates, different effects may appear, as in the case of a rotating disk, which generates inertial forces. That is what Einstein had to do, write his equations using tensors.

'One more arrow in Einstein's quiver then.'

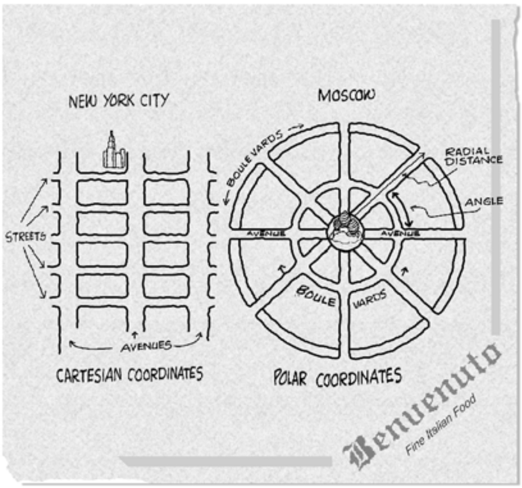
'Yes. We now come to the most basic ingredient of Einstein's theory, the concept of the metric functions,' announced George. 'The very essence of his curved spacetime! It therefore merits some detailed description.'

I felt that we were gradually converging towards the grand finale of Einstein's orchestrated efforts.

'Let us begin with the simplest case, as always, that of flat two-dimensional space,' George went on. 'Now, consider the example set down by George Gamow in his book, *One, Two, Three…Infinity*.'

'That is a delightful book, George.'

'It is indeed, Alfie. Let us elaborate a bit on what he writes in that book. New York City is covered with avenues and streets that are perpendicular to one another. They form a rectangular coordinate grid. Any building can be located by giving the distances along the avenues and the streets, which are the coordinates of that building. Furthermore, the distance between two buildings on the same avenue or the street is directly measured by the difference in the corresponding coordinate.'



'And the distance, as the crow flies, between two arbitrary buildings is given by squaring and adding the coordinate differences and then taking the square root of the sum,' I supplemented. 'This is quite simple and we have already discussed it.'

'Patience, my boy, it doesn't hurt to recapitulate what we already know,' counselled George. 'Now, Gamow goes on to the example of Moscow. He says that this old city grew around the central fortress of the Kremlin, with radially diverging streets and several concentric circular boulevards. These form circular polar coordinates, which give the location of any house or building.

Now, the radial distance is directly measured. However, suppose you want to know the distance between two houses along the same boulevard. You have to multiply their angular separation by the radial distance of the boulevard from the Kremlin. And this distance increases with the radius. To reiterate, the coordinate separation, namely the angular difference, does not measure the distance directly. It has to be multiplied by some function of the coordinates, in this case just by the radial distance. Is this clear, Alfie?'

'Absolutely, George,' I responded. 'Go on, then.'

'Now, we chose polar coordinates for convenience. Houses in Moscow could be located equally well using a rectangular coordinate grid, since we are dealing with the flat two-dimensional surface of the city. However, in the case of a curved space, we are forced to use curvilinear coordinates.'

'Such as in the case of the sphere for example,' I interjected. 'We come down to Earth again.'

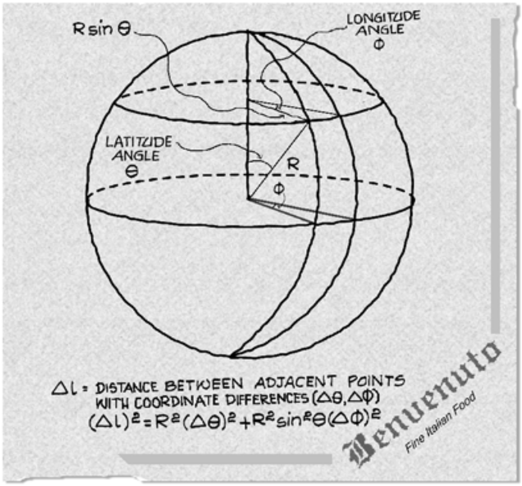
'Right you are. As we have seen before and as we shall see time and again, the sphere is covered with the lines of latitude and longitude as the coordinate grid.' George drew diagrams carefully to make things clear to me and added a few simple mathematical formulae. 'Look at the picture of the globe in any World Atlas. In mathematics and physics, we use a slightly different convention compared with that used on the globe. The latitude is indicated by the latitude angle, measured from pole to pole along a longitudinal line, instead of using the equator as the reference. Similarly, the longitude is given by the longitude angle measured from some reference line like the Greenwich Meridian, going all the way around the circle of latitude. These two angles are the coordinates that cover the sphere. All right then. Let us measure the actual distance between two points or cities with the same longitude or, in other words, on the same meridian.'

'The longitude is the same, that means the latitude changes between the two cities. All you have to do, is to multiply the difference in the angle of latitude by the radius of the globe,' I added.

'Exactly. You multiply the angle by the radius as you did in the case of Moscow. Again, take two cities with the same latitude. How do you determine the distance between them?'

'Well, now you have to multiply the difference in the angle of longitude, which changes between the two cities, by the radius of the circle of latitude.'

'Right again. This radius is a simple function of the radius of the sphere and the latitude angle as I have indicated on the diagram. As we move from the pole to the equator, the distance between two points on the same latitude increases.'



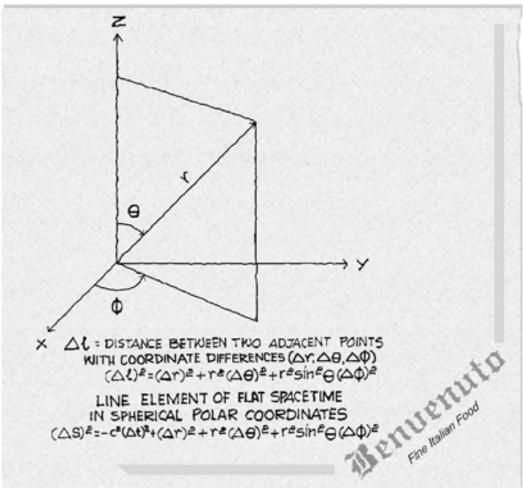
'Like the distance between two cities at the same latitude, say, in Russia as compared with the distance between two cities in India.'

'Now, take two arbitrary points very close to each other. How do we get the distance between them? Remember, we can consider them to be on a small flat plane tangential to the circle as we discussed right in the beginning.'

'Pythagoras strikes again,' I said. 'Square the longitudinal and the latitudinal separations between the two points and add them. That gives the square of the distance between the two points on the sphere.'

'Bravo, my boy,' nodded George. 'So, the square of the distance between two adjacent points on the sphere is *not* just the sum of the squares of the coordinates, namely the angles of longitude and latitude in the case of the sphere. But, each of these squares is multiplied by a suitable function of the coordinates. As we saw, these functions for the sphere turn out to be quite simple. But for an arbitrarily curved surface, say a potato for instance, they can be quite complicated.'

'What are these functions called?'



'They are called *metric functions*, Alfie, metric for measurement. They are the essence of the curved space I mentioned. The soul of space you might say. All geometrical properties of the space including its curvature may be derived from the metric functions. This is why I gave such an elaborate description of these functions. Incidentally, as you can easily see, in the case of rectangular coordinates in flat space, the metric is just unity since we simply add the squares of the coordinate differences.'

'George, in the flat two-dimensional space we had both Cartesian coordinates as in the case of New York and polar coordinates as with Moscow. How about flat three-dimensional space?'

'Well, we saw how it works in the case of a sphere of constant radius,' explained George. 'Now you let the radius change too. Then we have the square of the radial interval added to the angular part. This gives the length in three-dimensional flat space. And we have the polar coordinates in three dimensions.'

'All right. So, we have to multiply the coordinate intervals by suitable functions to get lengths when using curvilinear coordinates. How many such functions do we need in general then?'

'I was coming to that, Alfie, and you beat me to it. On an arbitrary two-dimensional surface we have in general three metric functions. In three dimensional space it is six.'

'How about four-dimensional space then?' Here we go, I thought, we are getting down to business.

'I expected that question,' smiled George. 'In order to describe four-dimensional curved space, we need in general ten functions at every point. Take spacetime as our precious example. In flat Minkowskian spacetime, metric functions are unity for space and negative of unity for time, provided you are using Cartesian coordinates. Even if you are using polar coordinates for the three-dimensional flat space all you have to do is subtract the square of the time distance to get the line element of the flat spacetime. In general relativity, when you are dealing with curved spacetime, in general, you need all the ten metric functions. Give these ten metric functions and you know the structure of spacetime completely. In other words, you know all about the equivalent gravitational field.'

'George, that seems like a vastly more complicated situation compared to Newtonian theory,' I remarked.

'So it is, Alfie,' agreed George. 'In Newtonian theory, gravitation is described by a single function, namely the gravitational potential. You know, right at the beginning of our discussions, we talked about potential energy. Gravitational potential at any given point is nothing but the gravitational potential energy of a particle of unit mass at that point. A simple differential equation relates this potential to the density of mass distribution that is producing the gravitational field. Solve this single equation and you get the potential. From this you can derive all the properties of the gravitational field at hand.'

'What happens in Einstein's theory instead?'

'One needs ten differential equations to determine the ten metric functions that represent the gravitational field now. They should be related not just to the density of ordinary mass. After all, energy is equivalent to mass too. Therefore, we must include the density distribution of all sorts of energy, like rotational energy, energy due to electromagnetic fields and so on.'

'Sounds awfully complicated to me,' I could appreciate the magnitude of the problem faced by Einstein. 'So, the major task before Einstein was to find the equations for the ten functions I suppose.'

'You are absolutely right,' said George. 'It took Einstein a tremendous amount of work and insight to arrive at those equations. It was a long and tortuous journey, Alfie, with so many twists and turns, so many false starts, and so much frustration. But in the end, by 1915, he had them. Ten equations for ten metric functions expressed as a single tensor equation. On the left we have what is known as the *Einstein tensor*, made up of the metric functions and their derivatives. Equated to it on the right is what we call the *energy-momentum tensor*, incorporating the mass-energy and the momenta of the sources.'

'In other words, you have spacetime curvature representing gravity on the left equated to the agency generating it on the right,' I summed up the equation that I had not even seen, and probably would never understand even if I were to see it, but for which I had some feeling by now.

George pondered before speaking up. 'You know how I feel whenever I look at this single equation which you so succinctly described, Alfie?' George reflected. 'I feel as though I am gazing upon two lofty pillars fortified by a marble slab connecting them, this simple structure holding up the entire edifice of Einstein's gravitational theory.'

George fell silent. I could imagine the awe he must feel at such a monumental theory as general relativity.

'Many physicists have paid glorious tributes to this beautiful theory, Alfie,' George remarked.

'I have read some of those compliments, George,' I said. 'For instance, J. J. Thomson, discoverer of the electron, is quoted to have characterized the general theory of relativity as one of the greatest – perhaps *the* greatest – achievements in the history of human thought.'

'Einstein expressed his own opinion on the beauty of the theory, you know,' said George.

'Oh, yes, I have read that too. *The theory is beautiful beyond comparison*, he said,' I quoted Einstein. 'Then again, *Hardly anyone who truly understands it will be able to escape the charm of the theory*.'

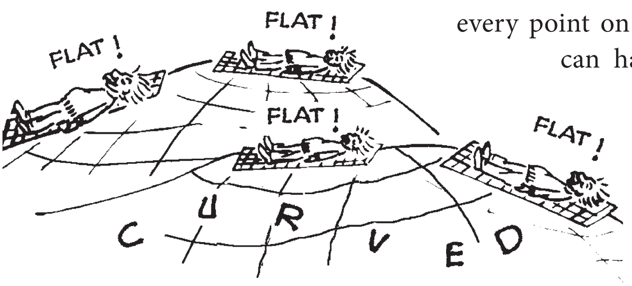
'Einstein was speaking from simple, objective conviction, not from hollow arrogance,' said George.

'Just like Newton promising to unveil the System of the World in his *Principia*, wasn't it?' I commented.

'That is the correct comparison, Alfie. Einstein realized the profundity of his theory. Compared to general relativity, the special theory of relativity was child's play, he said. Apparently, Paul Dirac, one of the great theoreticians of the twentieth century, told C. P. Snow that if the *special* theory hadn't been done by Einstein, it would have been done within three or four years by one of three different people, and probably all three more or less simultaneously. That theory was in the air. But Dirac went on to say that if the *general* theory hadn't been done by Einstein, then it probably wouldn't have been done to this day. No one can guess what the course of physics would have been in that case. No doubt about it, Alfie, the creation of general relativity was a unique event.'

One of the waiters brought the dessert and quietly withdrew. Fresh slices of peaches had been placed in a circle with a single strawberry at the centre. A lacework of whipped cream ran over the arrangement in a random pattern. The salad and the dessert seemed to form two different variations of a common theme. George and I savoured slowly this last part of a simple but lovely meal.

'Before we take a look at the achievements of Einstein's general relativity, we must discuss one aspect of curved space as on a sphere, which we touched upon earlier.'



'I remember it all right, George,' I said. 'At every point on the curved surface, you can have a small area that is tangential to the surface. And this little patch is flat. Am I right?'

'You have an abnormally sharp memory, Alfie. You must do something to correct it you know,' smiled George. 'Now take a ship that is sailing on the sea. The sea, when placid, looks flat. But as you sail on, the shoreline, the harbour, and the island on which you were carousing, will all disappear behind the horizon.

Then you know that the Earth is curved. As we saw, this happens in the case of gravitation too.'

'Yes, in a small freely falling frame you do not feel gravity,' I took off from George's analogy. 'The spacetime must therefore be flat within the small confines of the frame during a short interval of time. But if the frame is large enough, or if you wait long enough, you would feel the presence of gravity through tidal forces. Or in other words, you would know that the spacetime is curved.'

'Excellent, Alfie. You got it,' George appreciated my understanding.

'But I have a question though,' I said. 'In a freely falling frame, can there be other effects to show that there is no gravity acting?'

'Certainly. Suppose you have a light source on one wall of the Einstein elevator that is falling freely. And exactly opposite to the source, on the other wall, there is a receiver. What happens now is…'

'Don't tell me, I shall tell you,' I interrupted George in mid-sentence. 'The light ray bends due to gravity. However, since the elevator is falling with the same acceleration associated with the gravitational field, the ray will hit the receiver right on the dot. The observer will think that the light ray moved in a straight line.'

'Exactly. As a matter of fact, the observer sees all phenomena as described by special theory of relativity. For instance, he finds that the light velocity has the same old constant value.'

'Ah, I remember that Einstein derived his idea of light bending on the basis of a varying speed of light, didn't he?

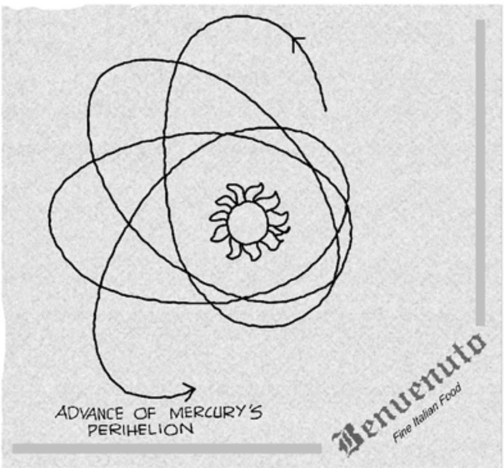
'Yes, on a large scale in the curved spacetime that happens. Sometimes, the choice of coordinates plays a role too, as we shall see. The fact that a freely falling observer sees a flat spacetime in a small region of it is known as the *local flatness property*. This turns out to be quite important in interpreting the results of general relativity. Of course, when you put together all these flat bits together, you would get a curved spacetime as in the case of a curved two-dimensional surface. We shall see the local flatness at work when we consider black holes.'

I found that all these analogies between two-dimensional surfaces and the spacetime curved by gravitation quite beautiful and revealing. I thought maybe if one knew enough mathematics of two-dimensional surfaces, it would be easier to understand that of spacetime too.

'Well, Alfie, Einstein had his theory ready in hand now. Based on it he made some concrete calculations. Three of these have come to be known as the classical tests of general relativity. First, he derived the gravitational redshift.' George started on the achievements of general relativity as he had promised.

'I thought he had already derived it in 1911 on the basis of the equivalence principle,' I remembered the paper George had shown me a while ago.

'Well, that was only within the Newtonian framework,' George clarified. 'Now he derived the formula using his full-blown general relativity. Since then, redshift has been well verified both astronomically and by Earth-bound experiments. For instance, gravitational redshift has been observed in the spectra of the Sun and white dwarfs. Then there are the terrestrial experiments. In the nineteen-sixties, R. V. Pound, G. A. Rebka, and J. L. Snider verified the redshift, or equivalently the blueshift, using the 22.5-metre high tower of the Jefferson Physical Laboratory at Harvard University. At the top of the tower, they placed a source of radiation, an unstable isotope of iron, which emits gamma rays by radioactive decay. The same isotope was used as the receiver at ground level to absorb the gamma rays. The latter would absorb a gamma ray provided its frequency was the same as when it was emitted. But a gamma ray falling from the top of the tower to the ground level, or in other words from lower gravity to a higher one, would have undergone a gravitational blueshift. This blueshift of the gamma ray was compensated for by making the source move vertically upwards, away from the receiver, thereby producing a Doppler redshift. The Doppler shift corresponding to the velocity that gave the maximum absorption was obviously equal to the gravitational blueshift. This way Einstein's redshift formula was verified.'



'Seems simple enough.'

'In principle, yes, Alfie. But in practice it was quite a challenging task. More accurate experiments have been carried out since then using signals emitted from a source carried by a rocket. Let us not go into details. The bottom line is that gravitational redshift has been well verified.'

'What was the next classical test?'

'Then there was the long-standing problem of the planet Mercury's orbit.'

'Aren't all planetary orbits ellipses according to Kepler?' I had assumed that this was an undisputed fact.

'True. But because of external influences this can change a bit,' George explained. 'It was a well-known observational fact that the orbit of Mercury was not a closed ellipse. The closest point of approach to the sun, or the perihelion of the orbit as it is called, advanced by about 5,600 seconds of arc per century. Most of this could be accounted for by the gravitational tugging of the other planets acting on Mercury. But there was a minute discrepancy of 43 seconds of arc per century. This could not be explained using Newtonian gravity. Einstein determined the general-relativistic effect in this problem after long, complicated calculations. Guess what he got.'

'Don't tell me that he got exactly the missing 43 seconds of arc!' It seemed incredible, yet to be expected of such a magnificent theory.

'You got it,' George nodded. 'That is precisely what he obtained! Here was a profound but highly complex theory and yet it yields exactly the miniscule amount that had bothered astronomers for a long time. Einstein wrote to a colleague that he was beside himself with joy for weeks.'

'No wonder. By the way, George, when you showed me Einstein's 1911 paper, you mentioned that he recalculated the bending of light in the gravitational field of the Sun. What happened?' I reminded George.

'I was just coming to that, Alfie. This was the third, and in a way the most important test of general relativity. The new value Einstein obtained for light bending, by applying his general relativity, turned out to be 1.75 seconds of arc, exactly twice the value he had obtained in 1911. This extra bit was due to the spacetime curvature effect.'

'I suppose this was verified by the eclipse observation as Einstein had suggested in his 1911 paper,' I prompted George.

'Yes, in a historic expedition led by Arthur Eddington, the distinguished astrophysicist who firmly believed in Einstein's theory,' George told the story. 'There happened to be a total solar eclipse in 1919 visible from a small island called *Principe* off the African coast. The sky was depressingly overcast and there seemed to be no hope of carrying out the observation. Then suddenly, just before the eclipse, the sky cleared. And Eddington's team succeeded in verifying Einstein's prediction of the bending of starlight. This was supported by the observations made by two other colleagues of Eddington from Sobral in Brazil.'

'Einstein must have been biting his nails waiting for the result of the eclipse expedition,' I speculated.

'Not at all,' George said. 'There are two statements he made, which are quite revealing as to his attitude towards his own theory. I am sure you must have read that Einstein had tremendous admiration for Max Planck, the originator of quantum theory. But let me show you what Einstein said about Planck in the context of the eclipse observation.'

As before, George took out a folded sheet of paper from the pile in front of him on which he had jotted down some quotations.

'Listen to what Einstein says about Planck,' said George and read out the quotation. '*He was one of the finest people I have ever known…but he really did not understand physics, because during the eclipse of 1919 he stayed up all night to see if it would confirm the bending of light by the gravitational field. If he had really understood the general theory of relativity, he would have gone to bed the way I did.*'

'That is unbelievable!' I exclaimed.

'Yes. Then again when he was asked in 1919 how he would have reacted if his theory had not been confirmed by the eclipse observation, he simply stated: *Then I would feel sorry for the good Lord. The theory is correct anyway.*'

'Such supreme confidence!' I remarked.

'Einstein had created the most beautiful theory ever, Alfie,' said George. 'I am sure he believed that beauty meant truth. But don't forget, this ineffable beauty covered the daunting complexity of the field equations.'

'Oh, yes, you explained their structure to me as they relate spacetime geometry to the gravitational sources,' I said.

'Right. But the two are not independent of each other. The sources determine the geometry of the spacetime. And the spacetime, in turn, dictates the behaviour of the sources. This has been described in a rather picturesque manner you know. The spacetime is not a mere passive stage on which the gravitational drama is enacted. The stage itself is one of the actors.'

'This was unheard of in the Newtonian theory, wasn't it?' This was indeed very strange.

'Absolutely. This poses a rather unusual problem, Alfie,' continued George. 'You cannot specify some fixed source and compute the spacetime it engenders or equivalently the gravitational field surrounding it. For instance, you cannot ask me to determine the field of, say, a potato. That can be done in Newtonian gravity. Just give me the mass distribution of the potato and I can in principle compute the gravitational field it produces. That is because the field does not affect the state of the potato. But I can't do this in general relativity. Potato and its gravitational field depend on each other inextricably.'

'So what do you do? Throw away all the potatoes in the world? You seem to be wrestling with a problem with both hands tied,' I commented.

'Throw away potatoes and chips? No way,' chuckled George. 'It is not all that bad, Alfie. What one does is to find exact solutions to Einstein's field equations assuming some simplifying conditions. Such as the existence of certain symmetries for instance. And hopefully one gets a solution. And with some luck, that solution would be physically significant, representing some realistic source.'

'There must be lots of exact solutions.'

'Oh, yes, plenty of them,' affirmed George. 'Generating exact solutions has become an industry in itself. Unfortunately, most of the known solutions are far from physically interesting. Nonetheless, a handful of them have turned out to be extremely important, just pure gold.'

'Such as?' I enquired.

'Such as, for instance, the cosmological solutions that describe the large-scale structure of the universe,' answered George and then added with his eyes gleaming. 'And then, Alfie, there are the exact solutions that correspond to the spacetimes of black holes. That is what we will be discussing in our next few sessions. Black holes and the entire universe emerging out of Einstein's equations! Think about that.'

'Fascinating! But you know, George Bernard Shaw, speaking at a banquet in England honouring Einstein, said: *Ptolemy made a universe, which lasted 1400 years. Newton also made a universe, which lasted 300 years. Einstein has made a universe, and I cannot tell you how long that will last!* What do you think of that, George?'

'Good old Bernard Shaw,' George laughed heartily. 'What he says of Ptolemy is true. We know that. As for Newton's universe, I would take it in its broadest sense, namely Newtonian physics.'

'Sorry to interrupt you, George. Some people believe that Einstein's relativity has completely dislodged Newtonian physics. Is that true?'

'Not at all!' George shook his head. 'In the case of velocities low compared to that of light, Einstein's special relativity is equivalent to Newtonian dynamics to a close approximation. And that is good enough for ordinary purposes. Similarly, the remarkable thing about general relativity is that it yields Newtonian gravity for weak gravitational fields, again as a close approximation. I mentioned this before when we discussed Newton, didn't I? Newtonian physics is not only adequate to describe the whole range of phenomena from molecular dynamics to galaxy formation, but it is also indispensable. General relativity, with all its complexities, would be of no practical use at all. With one definite exception, which we shall discuss later on. On the other hand, when we are dealing with strong gravitational fields like those of black holes or that of the entire universe, general relativity is indispensable.'

'And what about the fate of general relativity itself in the long run?' I asked.

'Well, Alfie, most of us believe that some other theory will be formulated someday, which will yield general relativity as an approximation,' answered George.

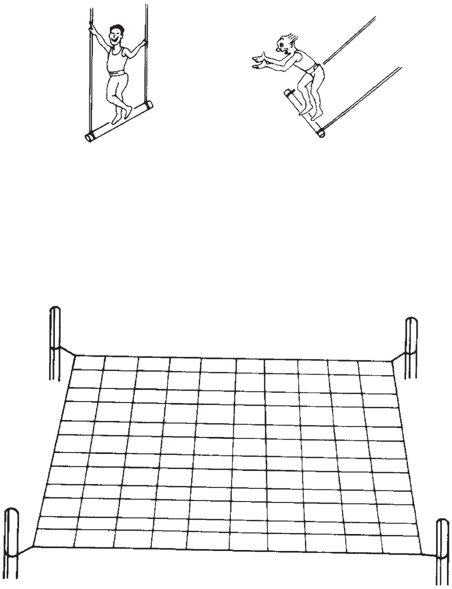
'So, in a way Bernard Shaw was right,' I pointed out.

'I suppose so,' said George. After a pause he added, 'You know how I would describe the work of these two giants who created their own versions of gravitational theory? Newton painted a beautiful portrait of gravitation on a flat canvas. And Einstein carved a unique sculpture of it out of spacetime.'

It was quiet in the restaurant now. Almost all the diners had left.

George pulled out another sheet of paper from the pile that had been progressively diminishing in size as I kept for myself the sheets George had referred to.

'Here is another cartoon for you, Alfie. It sort of sums up through a two-dimensional representation what we have been talking about,' said George. 'If you have noticed, we always illustrate our ideas by two-dimensional analogies. You know why? Although we live in a four dimensional world, our awareness is confined to three dimensions, our imagination to two, and our attitudes to one.'



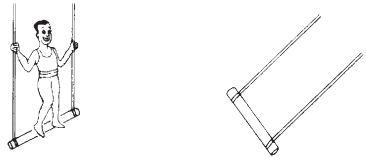
'Who said that?' I asked George.

George just smiled and shrugged. 'Take a look at the cartoon,' he said.

The cartoon consisted of two scenes in sequence involving two acrobats on their trapezes with a safety net stretched below.

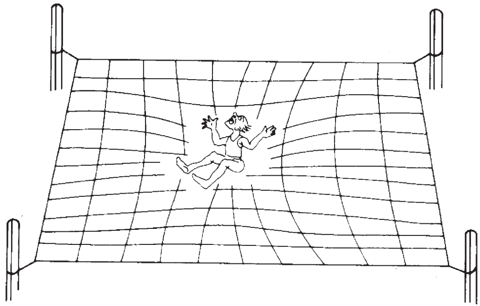
'The safety net represents the spacetime,' said George, explaining the contents of the cartoon. 'There is no one on it in the first picture, no gravitating matter, therefore no gravitation. So the net is flat like the spacetime of special relativity. The ropes, making up the net, form an orthogonal Cartesian coordinate grid covering the whole net. I can also arrange little cones, the light cones, all over the net perfectly identical to one another. So we have a representation of the flat spacetime of the special theory of relativity.'

'I notice some activity going on up on the trapezes,' I pointed my finger at the acrobats.



'Yes, indeed. One of the acrobats is about to jump. But the other one is standing without responding, grinning mischievously. We see the consequence in the second picture.'

The acrobat about to jump in the first picture had fallen onto the safety net. The other one was having a hearty laugh.



'Now, you see, a gravitating mass is present on the net,' George continued his commentary. 'The net has curved as a result. This is the spacetime of general relativity. The ropes of the net now form curvilinear coordinates. The curvature is higher near the gravitating body and diminishes as we move away from it. At sufficiently large distances the net is virtually flat and the ropes of the net form a Cartesian grid. Any object, say a ball, will roll towards the source because of the curvature.'

'Following a geodesic path,' I added.

'Right. I cannot arrange little cones, the light cones, as before identically all over the curved net. They may have to be turned in different directions and may have to be squeezed where the curvature is high. Now suppose the acrobat jumps up and down on the net. He would set up oscillations that would travel out along the net. In spacetime they are known as gravitational waves and were predicted by Einstein himself. We shall return to gravitational waves when we talk about black holes.'

'I have read that scientists are trying to detect these waves at several observatories all over the world,' I said.

'That is right. Another thing, Alfie. You remember earlier we talked about the problem of action at a distance and the transmission of gravitational effects in a vacuum without a medium?'

'Oh, yes, I do. You told me that even Newton thought that was absurd.'

'Right. Now general relativity had solved this problem completely. Spacetime itself is the medium that conveys gravitational effects by means of gravitational waves. And the effects are transmitted with the speed of light just like the electromagnetic radiation. Now, let us get back to the net analogy. If the mass of the fallen acrobat were to keep increasing, so would the curvature around him. Ultimately there will come a point, when any object placed near enough to him will roll down into the depression and will not be able to climb back. What do we have then?'

'A black hole of course!'

'That is what we will be discussing at our next meeting,' said George. He stretched throwing back his head. I knew he was tired but happy. He looked at his watch and exclaimed, 'Good heavens, Alfie. We have had a marathon session this evening, let us pack up and go.'

We got up, wished Bruno good night and made our way out of the little, cosy haven of a restaurant.

'You know, Alfie, Einstein's passage from special relativity to the general theory has been described as an intellectual odyssey,' George reflected as we strolled along at an easy pace. 'That immense journey witnessed moments of soaring excitement as well as abysmal frustration. But in the end it was an unprecedented triumph. What Einstein wrote about his lone voyage keeps repeating in my mind:

> *The years of anxious searching in the dark, with their intense longing, their alternations of confidence and exhaustions and the final emergence into the light – only those who have experienced it can understand it.'*

I thought about George's remarks. 'It is also like the ascent of an unconquered summit, the exploration of uncharted territory, isn't it, George?' I commented. 'It reminds me of what the Spanish poet Antonio Machado wrote:

> *Caminante, no hay camino*
> *Se hace camino al andar.*
>
> *Traveller, there is no path*
> *Paths are made by walking.'*

'How true, Alfie,' George concurred. 'In the course of his voyage or his ascent, Einstein's own philosophy changed. He had created his general relativity out of pure thought. Intellect alone had revealed reality. It was like the realization of the ancient Grecian dream, as Einstein himself was to comment. Einstein wanted to know by mathematical construction how God had put together the universe, the concepts underlying it and the laws that connected them. Of course, God was Einstein's handy word for Nature at its loftiest.'

'Einstein apparently told his young colleague Ernst Straus: *What really interests me is whether God could have created the world any differently; in other words, whether the demand for logical simplicity leaves any freedom at all.*'

'Yes. Perhaps in Einstein's mind, that logical simplicity demanded that gravity and electromagnetism be synthesized into a single entity. And one should be able to discover by reason alone how God would accomplish this, by following the same logic that God must have used. For decades, Einstein struggled relentlessly to achieve the unification of the two forces, but without success. Such unification has still remained an unfulfilled dream.'

'Let me tell you something similar to this, George. In Barcelona the great architect Antonio Gaudi started building his monumental cathedral *Sagrada Familia*,' I recalled. 'Perhaps Gaudi knew that he would never be able to finish it. It still remains unfinished. If asked when it would be completed, Gaudi would simply answer, *God is patient!*'

We had reached the point where we had to take our different paths – George towards the University and I back to my home.

George stopped and said, 'Whenever I think of the work of great men like Newton and Einstein, Alfie, I am reminded of the remark Werner Heisenberg, the brilliant quantum theorist, is said to have made: *I was lucky enough to look over the good Lord's shoulder while He was at work*. No, we may not be lucky enough to have looked over the good Lord's shoulder. But, we are at least fortunate enough to be able to look over the shoulders of those who have, like Newton and Einstein.'

After a brief silence George added, 'Well, Alfie, we have at last arrived at black holes. Let us talk about them in my office very soon. Good night and peace be with you.'

As I walked home, I came to the blind alley and stopped. Was there a light in the old store that had been boarded up? I thought I saw a faint glow illuminating one of the windowpanes. I looked again. There was no light, only darkness. It was probably just my imagination. I fondly remembered my experience in the old store and its owner Al. Suddenly a gust of chill wind blew from the alley and made me shiver. I gathered my jacket tightly about me and walked on.

Chapter 10

TUB TALK

Wisdom is not a product of schooling but of the lifelong attempt to acquire it, wrote Albert Einstein a year before his own life came to an end. And what a life he had led! I have been reading up a lot about Einstein as well as his own writings. The man was absolutely incredible, wasn't he? Having wandered around for a long time, he wrote to the physicist Max Born, *I myself have journeyed everywhere continuously – a stranger everywhere…A person like me is at home anywhere with those near and dear to him*. But his continuous journey came to an end eventually, and the last twenty years of his life he was to spend in the quiet serenity of Princeton. *A banishment to paradise*, he called it, adding, *I wished for this isolation all my life, and now I have finally achieved it here in Princeton.* No, I don't think those twenty years were banishment to a paradise of isolation at all. On the contrary, Einstein continued to be involved in so many different spheres of activity. Furthermore, he dispensed the wisdom he had acquired by his lifelong attempt, as he put it, through extensive writing and correspondence. George was right. He expressed his ideas and thoughts with incomparable beauty, elegance, and wit. *In the past*, he said, *it never occurred to me that every casual remark of mine would be snatched up and recorded. Otherwise I would have crept further into my shell.* I don't know. I am sure this was not false modesty, but at the same time I have a feeling that Einstein knew very well how quotable he was.

Well, enough of reading, I thought. It was time to relax a bit in my bathtub. The small supply of the special bubble bath beads was a little more than half finished. How I wished I could buy some more of it from Al. But Al's *All-in-One-Store* seemed to be closed down. I hoped it would open soon enough. For the present, I had to economize on those beads. As I lay in the bathwater, I watched the bubbles. Half of them were around me as usual. But the other half was concentrated at the water's edge. They were continuously hitting against the bathtub, rubbing it as they whirled around. Slowly, as a result, a tremor developed in the bathtub and grew into vibrations I could feel. Then, all of a sudden, I heard a deep, rumbling sound. I felt as though I was surrounded by it, or shall we say, I was bathed in it. To my surprise, that sound seemed to be transformed into a muffled voice. I thought I heard the words, 'Hello, boss.' I was startled to say the least.

'I am sorry I frightened you, boss. I haven't spoken in ages, you know. That is why my voice sounds so peculiar. It will get better as we go on, I am sure. By the way, this is your bathtub speaking.'

I could make out the words distinctly this time. But, for heaven's sake, my bathtub could speak? I couldn't believe it. Was I going mad?

'Surprised, are we? Can't blame you. After all, there aren't any other of my kind gifted with speech you know. But, of course, you must have heard of my ancestor, the Talking Tub of Tutankhamen. No? Again, can't blame you, since no such thing ever existed.'

There was gurgling laughter, following this ridiculous statement, which made the bathtub vibrate quite a bit and agitated the bathwater.

'Sorry, I should behave myself,' apologized the bathtub. 'I see you are confused, boss. Let me tell you about my unusual powers. I wasn't always like this you know. For a long time, I could not feel, I could not hear, let alone talk. My powers lay dormant, I suppose. But one day it happened. I was jolted out of my passive state by a blast of shock wave. There was an explosion. Later on I discovered the cause of that explosion. You see, for some reason or the other the Master had come into the kitchen. For some reason or the other he had exploded with laughter, as he often did. And that did the trick.'

God, this is getting worse and worse I thought. What was my bathtub doing in a kitchen? Who was this Master whose explosive laughter had induced the uncanny powers that the bathtub claimed to possess?

'Dear me, I have confused you even more,' said the bathtub. 'Well, I wasn't a bathtub to begin with you know. Once upon a time, I was a kitchen sink. Yes, that is why my dimensions are of a rather modest scale. I have grown a bit over the years though. I believe it is the effect of the expansion of the universe. Can you guess where I had been installed?'

Needless to say, I had absolutely no idea where the bathtub, which now professed to have been a kitchen sink, had been installed in its previous incarnation. And I was not going to indulge in futile guesswork.

'You will never guess, boss,' the bathtub assured me. 'I had been installed in one of the most famous houses in the world, One Hundred and Twelve, Mercer Street, Princeton, New Jersey, United States of America. Ever heard of it? The Master lived there, didn't he?'

Good Lord, my bathtub had been a kitchen sink in Einstein's house in Princeton! I felt a little dizzy to hear this incredible piece of information.

'I have heard that many have commented on the Master's roaring, booming, all-enveloping, cosmic laughter that echoed from wall to wall. Let me assure you it was true. That soulful laughter awakened me from my long slumber, boss. Then I learnt fast. I had an advantage you see. Me being a sink, my entire being was a receptacle for knowledge and an absorber of stimuli. I could pick up even the minute vibrations that came along the walls. Between you and me, boss, there is nothing more exciting than to find out what is being said in privacy behind closed doors. First I could only hear sound and feel the sensation of touch. But then slowly I became even sensitive to light, I think. I learnt that light could excite electrons, then why not those within me? I felt I could vaguely visualize forms. Maybe it was just my imagination. What does it matter? Is it possible that thoughts too produce waves, boss? I started reading the minds of people around me. You know very well spirits can read your mind. So can inanimate objects like me. If they are exposed to the proper environment that is. And what an environment I had! That house was filled with knowledge and wisdom. And above all, the genius of the Master, boss. Even the broom knew enough quantum theory, honest. If you had asked Master's opinion, maybe he would have told you that quantum theory should be confined to brooms. I am just joking, boss.'

Again there was a murmur of laughter. My bathtub talking about quantum theory, that too in such a cavalier fashion! This was too much.

'I know, boss, I shouldn't be so irreverent,' admitted the bathtub. 'And I talk too much, don't I? Can't help it. I have been silent too long and now the floodgates have opened. But you agree that I speak quite well. All Master's influence!'

Yes, the bathtub was quite articulate and maybe had a lot to tell.

'Although I was confined to the kitchen by cruel fate, I had a fairly good idea of everything that was going on in that house.'

How?, I wondered.

'How?' the bathtub answered my unspoken question. 'Like most of the things I came to know, by listening carefully to people who discussed things and remembering what I heard. Pretty smart, eh boss?'

Pretty smug, I thought.

'I shall ignore that comment that flashed through your mind,' the bathtub remarked. 'The most important room in that house was, needless to say, the Master's study. It was the centre of his universe. He did his research there, had discussions with his assistants, wrote, and dictated letters. He had his own exclusive bedroom. His wife Elsa had a separate one. You know why, boss? It was partly because of Master's snoring, which could set off seismic waves in the Earth's upper crust. Poor me, all night I had to endure the vicious vibrations that came down the walls and hit me like tidal waves. Well, as far as I was concerned, the most important room in the house was the kitchen, my own empire.'

The bathtub paused for effect and continued.

'Ah, the kitchen, my kitchen! The entire household carried on some activity or the other there. The household consisted of Master's wife Elsa, her daughter Margot, and Master's secretary Helen Dukas. I could recognize them all by the way they walked and talked. Of course, I waited eagerly to hear the wonderful stride of the Master and his voice. I must not forget two other members of the family, Chico the dog and Tiger the cat. Oh yes, all the humans were animal lovers, the Master included. I didn't have much interaction with Chico. But Tiger often crept into the kitchen. Sometimes he was a bit of a nuisance you know. He used to jump into me. Boss, a cat can jump *with* you, jump *at* you, and jump *on* you. But jump *into* you! It feels terrible. You can't imagine it.'

I had no intention of imagining a cat jumping *into* me, which sounded quite absurd.

'He was a moody tomcat, Tiger was. I remember once it was pouring outside. You know what, boss? Tiger should have been happy, since it was raining cats and dogs. Sorry for that silly remark. No, he was depressed, because he couldn't go out. Master was almost apologetic about it. I know what's wrong, dear fellow, he said, but I don't know how to turn it off. Another time, the Master came looking for Tiger so he could read him a letter. He had received it from the Chief Engineer of an American cargo boat. It seems the crew had given their cat the name Professor Albert Einstein. Crazy! I don't think Tiger was excited. He would have purred otherwise, yes? The Master wrote his reply in English, speaking out the words aloud. I remember it very well. *I am sending my heartfelt greetings to my namesake and also from our own tomcat who was very interested in the story and even a little jealous. The reason is that his own name Tiger does not express, as in your case, the close kinship to the Einstein family. With kind greetings to you, to my namesake's foster parents and to my namesake himself.* The Master laughed and left.'

The bathtub paused. I caught myself thinking that it was remembering the good old days! How could I even imagine that my bathtub functioned like a living thing? But I couldn't help it.

'Enough of cats and dogs,' the bathtub spoke again. 'Now for some human interest. For more than twenty years Elsa had taken care of the Master, boss. She was strict that lady, sometimes treating the Master like a child. You know what she used to say? He can have coffee for breakfast. But in the evening only Sanka, otherwise he will not sleep. And, of course, absolutely no cigars. She enjoyed the Master's fame all right. But you know what she said? Living with a genius was exhausting and complicated. Can't blame her, can we, boss? Poor Elsa, her life in our house on Mercer Street was to be very short. People started talking in low voices. Something about problem with her heart and kidneys. The Master was terribly depressed by Elsa's illness. How could he find peace? Just work, work, and work, that is what he did. At night he wandered all over the house. I could follow every footstep of his, heavy footsteps they were, you know. I felt awfully sorry for both of them. But what could I do, boss, me a lowly kitchen sink fixed in one place? Nothing. Soon Elsa's condition became worse. I could hear her moan. I could hear doctors come and go. Heavy things moved in, medical equipment they said. There were whispers all the time. Someone said that the ground floor looked like a hospital ward. No use, boss, no use. Elsa passed away. They said she was proud to the end of her husband's achievements.'

The bathtub fell silent. Reliving sad memories with pain, I supposed.

'After three years, Master's sister Maja, moved into our home,' continued the bathtub. 'They were very close to each other, brother and sister. She used to recall something very funny. She had heard it from her parents long, long ago. When she was born, her parents had told the news to her two-and-a-half-year-old brother. You have a new toy to play with, they said. And when he saw the baby, he had asked, but where are the wheels? Lovely, no, boss? You know what? Her voice and the way she spoke sounded so much like the Master. It gave me the creeps. As I told you, we had another lady in our house, Helen Dukas. Wonderful she was. After Elsa died, Helen ran the place. Did everything, you know. Including cooking, usually simple meals, often spaghetti. I should know, since I got to taste the leftovers, didn't I? Sometimes, that long spaghetti got stuck in my throat. That I didn't like at all. Helen was also housekeeper and most important Master's secretary, took care of everything he needed. Controlled the visitors strictly. You know why? So the Master could work. And work he did. All the time. Wrote hundreds of letters to all kinds of people. Small people, big people, kings and queens. Discussing science, giving advice, helping worthy causes. Most of all doing science, living it day and night. Whenever he got a new idea, which was quite often, I was hit by a blast of his brainwave. I caught some of his idea too. Thinking is what makes science, eh boss?'

Oh, yes, indeed, I thought. Way back, about a year before Eddington verified his general theory of relativity, Einstein had written, *The mainspring of scientific thought is not an external goal toward which one must strive, but the pleasure of thinking.*

'Such wonderful things the Master used to say, and so well too,' the bathtub continued its account. 'I heard people quoting from Master's old letters and writings. Sometimes the Master himself would repeat what he had said earlier. Oh, it was so nice to hear him do that, boss. But I could feel he was straining himself a lot. He used to say he wanted to do something very important. He called it unification.'

Ah, Einstein's Holy Grail, the unification of gravitation and electromagnetism. I could very well imagine how hard he must have been working towards this goal.

'The Master worked hard on this problem with help from some assistants he had at different times,' the bathtub went on. 'They all worked at the Institute, as they called it. Quite often they came home to work. Let me recall their names, those young and energetic chaps. Oh, yes, there were these three assistants, Bergmann, Bargmann, and Hoffmann. There was lot of confusion and jokes about the first two with almost same name. There was this other young man, Strauss. You know what he said? He thought he would never get the job as assistant to the Master, since his name did not end in Mann like the other three. Funny, no? The Master interviewed Strauss in his study. Halfway through it, he came down. He asked Helen if she knew anything about this young man. Helen told him something I never understood. She said that it so happened that she had been present at his, let me remember the word, circumcision, yes, that is what she said. Nobody ever explained what this word meant, although everyone laughed. Anyway the Master said that was recommendation enough, and hired Strauss right away.'

The bathtub gurgled for a long time probably remembering all the sniggering it must have heard.

'I remember something really wonderful. Once the Master came into the kitchen along with one of his assistants, Bergmann I think. He offered to do the dishes for Helen. After half an hour or so, Helen came back. I think she was hoping that the job would be finished by then. What does she find? Bergmann is holding a towel and a plate, the very first one, in midair frozen in the act of drying it. The Master is holding the second one, immersed in the water they had filled me with. Both totally engrossed in their discussion. Helen drove them away and completed the job. But how I wished they had stayed on, boss. To have the Master so near me for so long! And to feel his touch all the time.'

The bathtub fell silent for a while, probably savouring those rare blissful moments of the past. Then it spoke in a serious, resonant voice.

'In a four-dimensional spacetime, the metric tensor has sixteen components, ten of which are symmetric and represent gravitation through the geometry of the spacetime, while the other six anti-symmetric components may, hopefully, be identified with the components of Maxwell's electromagnetic field tensor.'

I was completely baffled. The bathtub burst out with its liquid laughter, shaking violently and splashing the bathwater all over.

'Sorry, boss. As someone said, maybe the Master, like many scientists I don't know what I am talking about,' the bathtub apologized. 'But, you see, what a deadly dose of physics I have absorbed. The Master came up with so many ideas for this unification of his! Whenever they fizzled out, his assistants would get terribly depressed. No boss, the Master never felt bad by failure. The world has waited all these years, he would say, let it wait for a few more months. Whenever he came up against a stone wall, he would say in his funny kind of way, *I vill a little tink*. He would pace up and down, go round and round, hum a tune, come down to the kitchen, go back to the study. They said he would be twirling a lock of hair on his forehead all the time. And a new idea would hit him, jolting me as I told you. The Master wanted to publish even his failed attempts. What for? someone asked. So that no other fool makes the same mistakes, the Master would say. What makes a person so strong, boss? I could never understand.'

Yes, Einstein would even joke about his own theory. He wrote to the mathematician Elie Cartan: *For the moment, this theory seems to me to be like a starved ape who, after a long search, has found an amazing coconut, but cannot open it; so he doesn't even know whether there is anything inside.*

'I want to tell you something that confused me a lot, boss. Maybe you could help,' the bathtub seemed to be starting up on a new topic. 'The Master talked a lot about someone called God. God does this, God does that. God doesn't do this, God doesn't do that. Who was he? I decided he must be a good friend of the Master. But then, I knew everyone who came into our house, didn't I? I never heard this guy God's footsteps. So, he never came home. Strange. God does not play dice, the Master said. Dice, what is that? I came to know that playing dice meant people made money or lost it and it was bad. God didn't do that. Good. God is not malicious, the Master said. That was nice. But you know what? When he was having difficulties with this unification stuff, the Master told Bargmann: I have second thoughts, maybe God *is* malicious. Then this God is not nice after all, I thought. But he chuckled, the Master did, so maybe he was only joking. Very confusing, don't you agree? But finally I think I understood, boss. The Master said God showed himself in the, what was the word he used, yes, harmony of the universe. So, everything the Master studied was God to him. There must have been another God, too. I clearly remember what the Master said another time. I kept thinking about it. He said why should God punish his children for their stupidities, for which he himself should be held responsible. Only his non-existence could excuse him. The Master loved children you know. Punishing children, the little ones, is very bad. But what did it matter anyway? This God didn't exist. That was it then. Still, the whole thing was very confusing, don't you agree?'

Yes, I agree, I thought. God *is* confusing and so is religion.

'Oh, yes, religion, the Master talked a lot about that too.' It looked like the bathtub had read my mind as it claimed to be able to do. 'Again a bit confusing to me in the beginning, all this science, God, and religion mixed up. The Master said he felt awe for his God and for the way this God showed himself. And his religion came from this awe. What is this awe business, I wondered. Then I knew. It is the same thing I felt for my Master. Then I must have had my own religion too, eh boss?'

The bathtub paused before continuing in an amused tone.

'The Master called it the cosmic religion. Maybe not all people liked this religion, you know. One day, the Master came into the kitchen and told Helen what some Bishop had said: "There is only one fault with his cosmic religion; he put an extra letter in the word cosmic – the letter s!" The Master laughed and laughed.'

The bathtub fell silent for a long while. Perhaps it was collecting its thoughts. Maybe it needed rest from time to time, since it said it had not spoken for a long time.

'It was all so nice, boss, the Master working hard with his boys, talking about so many things and, most of all, having his hearty laughs,' the bathtub resumed its story. 'But then things changed. Bad times came, boss. A big war was on, they said. Everyone was gloomy, speaking in hushed voices. The women were glued to the radio trying to catch the latest news. There was a shortage of things. Even water. I think it suited the Master. He hated taking baths, you know. Elsa used to force him to do it. But I liked to be clean. But what could I do? With not much water, they didn't always wash me. Nothing to complain about, boss, not really. There were such horrible things happening. First time I heard the words like death and killing. One day, the Master said some old student of his was coming. What is a student, boss? One who learns from you, right? I learnt a lot from the Master, didn't I? Every time I heard him, he gave me knowledge. Every time he touched me, magic flowed from his fingers into me and filled me up, just like water. Whenever he thought, I got ideas directly from him. All this you humans can't do, can you? Someday, maybe, someday. Anyway, I am Master's student am I not? Come to think of it, boss, so are you, since you read so much of what the Master had to say.'

The bathtub paused for a moment and continued.

'Sorry, boss, where was I? Yes, Master's old student. Leo Szilard was the name. The Master and this student had once thought of a new kind of refrigerator, it seems. Can you imagine the Master selling refrigerators? Oh, no. But the student was coming for a serious business, the way the Master talked. It was about a bomb, something very powerful. But the Master didn't meet this Szilard at our home. Otherwise I could have told you all sorts of details. The Master was on vacation you see, doing some sailing, which he liked a lot. The ladies in the house said the Master wrote a letter to the President. This President must be a very big man, I thought, the way they mentioned him. How could anyone be bigger than the Master, I wondered.'

The bathtub paused. I felt that all this talk of the war had brought back some depressing memories.

'The bomb was made, we learnt. Now the Master worried a lot. What if it fell into the hands of foolish or bad people? What if it was misused? What if it killed innocent people? Once again he wrote a letter to the President so Szilard could go and talk about all this with the President. But how can you tell how things turn out in this world, boss? The President died, it seems. Master's letter was not even opened. Then it happened. The bomb was dropped, killing lots and lots of people. Helen heard the news on the radio. The Master came down from his bedroom for his afternoon tea. And she told him. He cried out, "Oh Weh!" It meant "Alas" I learnt. One word, boss, one word that was heart-wrenching. Just a manner of speaking, boss, I know I have no heart like humans. But that word poured out all of Master's anguish.'

Yes, I knew. Later on, Einstein had written to another peace-loving scientist, Linus Pauling: *I made one mistake in my life – when I signed that letter to President Roosevelt advocating that the bomb should be built. But perhaps I can be forgiven for that because we all felt that there was a high probability that the*

Germans were working on the problem and they might succeed and use the atomic bomb to become the master race. In private, he said that he could have burnt the hand that had signed that letter.

The bathtub fell into a long spell of silence. But I could feel mild tremors that ran along its body.

'He was a most peace-loving person, the Master was,' the bathtub resumed. 'Whenever he spoke of peace, he never failed to mention this man with an unusual name. Grandee, was it? No, it was Gandhi I think. The Master admired him so much, you know. He kept his picture in his study. The Master once said that this man's followers called him the Mahatma, whatever that means. You know about him, boss?'

Of course I knew about him. I had read quite a bit about Gandhi, Mohandas Karamchand Gandhi, who was called the Mahatma or the Great Soul. Gandhi had advocated and practised total non-violence. His weapon, innocuous but immensely potent, was non-cooperation. I knew that Einstein had tremendous admiration for Gandhi. On the occasion of Gandhi's seventieth birthday, he had written: *Generations to come, it may well be, will scarce believe that such a one as this ever in flesh and blood walked upon this earth.* Well, I had always thought that the same could apply to Einstein himself.

'Yes, the Master talked a lot about Gandhi,' the bathtub continued. 'He said that peace could come to the whole world only by Gandhi's methods. He was so happy when Gandhi's country won freedom by his methods. But, then, what happens? Some misguided fanatic goes and kills Gandhi. The Master was heartbroken, I can tell you that. I was stuck in the kitchen, wasn't I? Sometimes it made me sad. But other times, I felt lucky. You know why? Out there in the world, there seemed to be no sense at all. I often wondered about that, boss.'

Haven't we all, I thought. Perhaps it was a few people like Gandhi and Einstein who brought some sense to this world. In a madhouse, the sane are in the minority after all.

'Madness, boss, madness. Worry upon worry. I could feel the Master's sadness. I could feel it in his strained voice. I could feel it in his heavy steps. I could feel it in his hollow laughter. From time to time, the harsh voice of this senator called McCarthy came on the radio. He talked about some one called communist. Hiding in every nook and corner. Plotting to destroy the country. All nonsense, I knew. Many had a horrible time as a result. The Master's advice was to fight this madness by Gandhi's methods. The Master also said this bomb business should be controlled by all countries. Then it started. Postcards full of hatred came by mail. Get out of our country and go to Russia, they shouted.

May you die in agony, they screamed. Ungrateful refugee, they yelled. Helen kept all those things just as she kept all other letters. The Master was not angry, boss, only sad, infinitely sad.'

Photographs of Einstein taken at that time show his abysmal anguish. Furrowed brows, sad eyes, and an expression of deep sorrow. What a contrast to the pictures of his younger days!

'Yes, boss, people do grow old, don't they?' mused the bathtub. 'I have aged too. Look at me. Here and there, my skin has cracked and parts of me have become discoloured. I have both yellowed and mellowed with age, as you would put it. You should have seen me in my youth, boss. If I got angry, I would splash around violently.'

Thank heavens I didn't meet you when you were young, I thought. I would be spending half of my life mopping up the floor after each of the tub-tantrums.

'Not a very complimentary thought, boss, which I shall ignore as usual,' said the bathtub with a giggle. 'Well, aging is for us. The Master felt that people like him didn't grow old at all. You know why? Because, they are always like curious children standing before the great Mystery into which they were born. His words, boss, not mine. Anyway, even old age has very beautiful moments, the Master said. A young old age he called it. His recipe for it: Do not take yourself or the next person seriously and keep your good humour.'

I knew that Einstein did not take himself seriously. He made light of his own fame, often joking about it.

'The master might not have taken himself seriously,' the bathtub continued from where it had left off. 'But I can't say that he did not take others seriously. Let me give an example. Once some big man came home for dinner. The Master insisted that his chauffeur should also be invited to eat with the rest. Not only that, boss. The master sat next to him and chatted so nicely. But the poor man, he felt quite awkward. You see, boss, the Master felt very strongly that all human beings are equal. What a pity he forgot kitchen sinks, I felt.' The bathtub giggled again and continued. 'He was very nice to people whom others ignored. He listened patiently to physicists and inventors with funny ideas. Helped them sort out things you know. Of course, he enjoyed the company of people interested in different things. Especially people who made him happy, who made him laugh.'

After a moment's hesitation, the bathtub added almost in a whisper, 'The Master would have liked you, boss. He would have liked your curiosity, your being gentle, and your sense of humour.' I was deeply touched. The bathtub rested for a while before starting up again.

'Children, boss, children, the future of the world,' the bathtub exclaimed exuberantly. 'What is childhood, boss? Did I have one? I was just made, not born, right? So, no childhood. But look at it this way. I learnt about things starting from nothing. Just like a child. Then that was my childhood. Oh, well, let me get on with my story. There were no children in our home. I didn't have much experience with them at first. But the Master loved them. One day a little ten-year old girl walked into our house. Helen said how sweet she was. Sweet? I knew what that meant. I had tasted left over cake and such things, hadn't I? But this was the first time I found out how sweet sound could be too. Well, I realized how sound can be hot, sour, and bitter also. To continue my story, this kid was so shy at first. Somebody had told her that a very big mathematician lived in our house. He was also a very kind man. So she came for help with her homework. The Master was so happy, boss. He explained everything to her in a simple manner. The kid started coming regularly. Then her mother came. She felt terrible about her daughter bothering the great man. She wanted to apologize. The Master laughed. You know what he told that poor, worried mother? He had learnt more from talking to the child than she had from him! Amazing, no, boss?'

I had heard this anecdote before, but I was not sure it was true. Here was the confirmation. I trusted my bathtub all right. In any event what does it matter? Usage turns a legend into truth, doesn't it?

'Thanks, boss, for having faith in my word,' the bathtub read my thought. 'The Master never ignored a single letter written by the young. He often read the letters aloud thoroughly enjoying their innocence. He always replied promptly. He sent nice little notes to the children. Some kids wrote to him that they were shocked. Why? Because their teacher told them that human beings belonged to the animal kingdom. They wanted expert opinion on this matter. The Master patiently explained to them why this was so. He was around seventy-four at that time. A year earlier, he got a letter from the Sixth Form Society as they called themselves. They were from a grammar school in England. They wrote they had conferred upon the Master the Rectorship of their group. That of course involved no duties. The Master was delighted. He told Helen he accepted this honour with pride. He said he was an old gypsy. But old age liked respectability. Another time, a letter came saying this farmer from Idaho had given his son the name Albert. The Master wrote a beautiful little note to him. You know what happened next? A big sack of Idaho potatoes landed on our doorstep – a token of appreciation from the farmer. Helen had a tough time cooking all those potatoes. And poor me, I had to taste potato skin for a long time too.' The bathtub made a peculiar sound, which, I suppose, indicated its distaste and added, 'the Master was deeply touched when he received a tie clasp and a pair of cufflinks sent by children of an elementary school. It was a present for his seventy-sixth birthday. Sadly it was to be his last birthday you know.'

I closed my eyes, enjoying the warmth of the water around me leaning my head against the bathtub. After all, I was taking a bath, wasn't I? Slowly the rim of the bathtub started vibrating gently. The vibrations were picked up by the entire body of the bathtub producing soothing, ethereal notes. It was an eerie feeling to be immersed in this strange, lovely music.

'Lovely, isn't it, boss?' the bathtub spoke against the background of the music that had become soft and low. 'No one makes such music. You know why? Because I am both the instrument and the player.'

The bathtub was producing its music by the same principle as that of the glass harmonica. I had myself experimented with the glass harmonica by filling several glasses of different sizes with water. By running my finger along the rims with moistened fingers I could produce notes that were quite unusual too. I had even heard music written for the glass harmonica by no less a composer than Mozart.

'Ah, Mozart, the Master's favourite composer!' exclaimed the bathtub happily. 'He had lovely things to say about Mozart's music. It was so pure and beautiful that he saw it as a reflection of the inner beauty of the universe, he said. Mozart discovered and revealed the music that already filled the universe. The Master made such nice music on his violin, boss. It floated in the air. It filled me up. I resonated with it. Ah, then I found my soul you know, even if it didn't exist. Sometimes, Elsa and the Master used to talk about their days in Berlin. They remembered the beautiful, old-style music room in their house there. Yet, the Master preferred to relax after work by playing his violin in the kitchen. He felt that the kitchen had better acoustics. How I wished he played music all the time in our own kitchen too. He loved his violin. He called her Lina, his beloved Lina.'

The bathtub had stopped making its music. I think it wanted to concentrate on its experience of the past.

'Boss, a most memorable event took place in 1952, the year the Master reached the age of seventy-three,' the bathtub recalled. 'A bunch of musicians came home. Very young they were. They wanted to play music specially for the Master. What was the name of this group? Let me remember, yes, they called themselves the Juilliard String Quartet. The Master chose to listen in the room adjoining the one where they played. He didn't want any visual distraction, he explained. They played music by Beethoven and someone called Bartok. I hadn't heard this Bartok before. The Master enjoyed the music all right. Then these young chaps launched their surprise attack. They pulled out two pieces of music by Mozart. They told the Master it would give them great joy to make music with him. He protested. He said he had not played for years because of a hand injury. Finally, the enthusiasm of youth won, boss. One of the musicians handed over his violin to the Master. He picked up a viola in its place. I could gather all this from the excited remarks they were making. The Master said he would choose the great G minor quintet as he called it. The chairs rustled. The musicians re-grouped around the Master. As the Master placed the bow on the violin, his fragile out-of-practice hands faltered for a moment. Then he was back on form. His concentration was awesome, boss. How can I describe what followed! The majestic, brooding music flowed on. Slow, slower, and slower crept each successive movement. The mood of the musicians, as they finished the quintet, was – what was the word they used, oh yes – beatific. But it was late. Those wonderful boys, who had given the Master so much joy, gathered their instruments, reluctantly bidding goodbye. I could read the Master's mind. His thoughts were still savouring Mozart's music in an unhurried manner. Before those young musicians left, he remarked that music should not follow the frantic pace of life. Music had its own tempo.'

The silence that followed was long. The powerful feelings of the past must have surfaced once again.

'The tempo of music one can control, boss,' the bathtub reflected. 'But what about the tempo of time? Can you control it? The Master was aging. He had his own health problems, you know. Elsa used to have strict control over his smoking. He loved to smoke. He used to say smoking contributes to a calm and objective judgment of human affairs. I don't know about that. I didn't smoke, did I? I suspect he smoked in secret, the cunning Master. He took his ill health in good humour like all things he did. A box of candy was being passed around after dinner one evening. He just took a deep sniff. You see, that's all my doctor allows me to do, he explained roaring with laughter. That was the Master for you. But how long can one postpone the inevitable, boss?'

The bathtub made a sound that resembled a long, deep sigh.

'As his friends and loved ones departed, the Master could feel it coming,' said the bathtub in a low voice. 'Elsa was long gone. Now it was Maja's turn. She had suffered a stroke. They said it had led to degenerating paralysis. I don't know what that meant. All I know is that she didn't come to my kitchen any more. She lived on for another five years. When she passed away, the Master was in his seventy-second year. During Maja's last years, the Master used to read to her every evening. She couldn't speak almost. I could just make out her feeble voice coming down the walls from her room. They said, strangely enough, her intelligence had barely suffered.'

I had read that Einstein loved his sister very dearly. Her death was a cruel blow to him in his old age as was that of his dear friend Besso later on.

'The Master missed Maja more than one could imagine,' the bathtub continued. 'Yet, he was at peace. He knew the reality of death. When Maja died, Margot was in great sorrow too. The Master consoled her. He told her, look deep, deep into nature, and then you will understand. The Master used to say so many things about death. Brief is this existence, the Master said, like a brief visit in a strange house. And death comes as a release, like an old debt to be discharged.'

I had read about Einstein's last days. He had been suffering for a long time from the hardening of the aorta, which had developed an aneurysm. There was ever increasing pain now. Einstein was clear about how it should end: *I want to go when I want. It is tasteless to prolong life artificially. I have done my share; it is time to go. I will do it elegantly.*

'The Master was in pain, boss, terrible pain,' the bathtub recalled those days of April, the cruellest month. 'But he wouldn't see the doctor. Helen telephoned Margot. Margot was herself ill. She was in the local hospital. Only when the Master collapsed did the doctors arrive. There was a leakage from the hardened aorta they said. Something called aneurysm it seems. They remarked that the Master was very stoic and his usual shy self. I don't know what all this meant, boss. I am just repeating what I heard. Next day, the Master was in horrible pain again. God, I could feel it, boss. I wished I could help. But what could I possibly do? They decided to move him to the hospital. For the last time, the Master was leaving our home on Mercer Street.'

There was a gulping sound followed by a short spell of silence.

'I learnt about what was happening in the hospital from bits of hushed conversation I could hear,' the bathtub resumed its account of Einstein's last days. 'Margot was brought in to see the Master. She was a in a wheelchair. She could not recognize him at first, she said later. So changed was he from pain and lack of blood in his face. But his manner was the same. He was glad that Margot was looking a little better. He joked with her. He talked with perfect calm. Even with slight humour about the doctors. He was patiently waiting for the end. On Sunday evening, the Master fell asleep peacefully. On the eighteenth of April in the year nineteen fifty-five, a little more than an hour after midnight, what they called the aneurysm, it burst and the heart stopped beating.'

There was a lull again before the bathtub resumed.

'Before his departure from this world, it seems that the Master had said, I have finished my task here. Yes, the task was finished. The Master had become part of the harmony of the universe.'

The bathtub shook as tremors passed through its body. And then all was quiet.

I had not realized that I had my eyes closed for a long time. Had I been dreaming? I felt drained, but at peace. Slowly I got out of the bathtub, wrapped myself in my dressing-gown, and made my way towards my bedroom. Just as I was about to leave the bathroom, I stopped short. Had I heard the words, 'Good night, boss,' in a strange whispered voice? Startled, I turned around sharply. Nothing. All I could see was my bathtub with some bathwater splashed around. That was unusual as I am always quite careful. I flopped down on my bed and fell immediately into a long, dreamless sleep.

Chapter 11

THE FIRST SOLUTION AND THE LAST STATEMENT

I was to meet George in his office at the university. The physics building, where he works, consists of two inter-connected wings, the old building to which the new one has been added. George had opted to remain in the older part. He prefers the massive wooden doors with their shiny brass knobs worn smooth by usage, and the solid, old-fashioned furniture to the modern trappings of the new construction. George loves what he calls the ambience of antiquity that pervades the dimly lit corridors. He says he can feel the presence of his distinguished predecessors who once walked those corridors and worked in the old building.

I knocked on George's door and entered. Stroking his chin in deep concentration, George was standing in front of the blackboard gazing at several equations written on it. I felt that I was intruding upon some important work of his.

George must have sensed my feeling as he spoke to me warmly still gazing at the equations, 'Good to see you, Alfie. Let me just jot down a couple of points and I will be with you.' He scribbled a few words and some mathematical symbols on the blackboard and came over to greet me.

'You have to give the third degree to mathematical equations, you know,' said George. 'Stare long and hard at them. And sooner or later, they break down and confess all their secrets to you.'

This was the first time I had come to George's office and he watched me with amusement as I looked around. He had inherited an immense, ancient wooden desk with many drawers, and a matching chair. The two smaller chairs in front of the desk, meant for visitors, were stacked with science journals.

'Those journals are quite comfortable to sit on, Alfie,' George laughed. 'But I cannot say the same thing about reading them though.'

Set apart from George's desk was a large table piled up with typed and photocopied articles, notes, sheets of paper with jottings on them, and little yellow stickers carrying comments spread all over. It looked like a huge mess to me.

'I call that my organized disorder, Alfie,' commented George. I know every tiny bit in that pile, what it is and where it is. I can pull out instantaneously whatever I want.'

George's bulletin board too was overflowing with announcements of campus events and seminars, official notices, and, amidst all this, quotations and cartoons. In the corner next to the blackboard was a low, round table, with a few comfortable chairs around it. The table, in striking contrast to the rest of the office, was uncluttered with a lone writing pad and some pens lying on it. There was also a neatly arranged stack of photocopies of printed material. George led me to this cosy corner where obviously he carried on his discussions with students and colleagues.

'Well, Alfie, what have you been up to?' asked George. 'Gorging yourself on black holes, I suppose. Normally, it is the black hole that devours things, you know.'

'Not really, George,' I answered. 'I did read a bit about black holes here and there. But why should I exert myself when I am going to learn all about them straight from the race horse's mouth?'

'That is laziness disguised as a compliment, Alfie. Thanks anyway,' laughed George. 'Before we begin on black holes, refresh my fading memory as to what we have learnt so far.'

'To begin with, you told me about stellar evolution ending with three states of permanent rest – the white dwarf, the neutron star, and finally the black hole.'

'Then what?' asked George. I knew George was not testing me. 'Never test or judge another,' he says, 'lest you should be tested and judged.' He was just setting the stage for further discussion.

'The black hole, you stated, was purely an outcome of Einstein's general theory of relativity. Nevertheless, one must understand Newtonian gravity first to appreciate Einstein's radical new theory. This in turn calls for knowledge of his special theory of relativity and the idea of spacetime. That is the gist of what you have told me so far.'

'Excellent. I assume you remember all the details.'

'Not just remember, but everything has been absorbed and assimilated.'

'In that case we are ready to plunge headlong into the black holes.' George opened the writing pad and picked up a pen. As usual, throughout our conversation he would jot down salient points including simple mathematical formulas and draw illustrative diagrams.

'Let us backtrack a bit to Newtonian gravitation,' George began.

'Back to Newton again?' I asked in surprise.

'Yes, Alfie, Newton is the alpha of gravitation, even if we do not know who omega will be, if ever there will be one,' said George. 'Just on the basis of Newton's law of gravitation, two scientists in the late eighteenth century made a rather unusual speculation. They thought of celestial bodies so condensed that they did not allow light to escape. Consequently, such objects had to be invisible, they argued. The first of these two scientists was Reverend John Michell in England.'

'A priest no less?'

'Yes, Michell was also a geologist,' answered George. 'He was one of the founders of the science of seismology, you know. In a paper he read to the Royal Society in 1783 and published later, he discussed the possible existence of invisible stars.'

'Who was the second one?'

'Laplace,' answered George.

'Well, Pierre-Simon Laplace, who has been hailed as the Newton of France. We have already brushed against him when we talked about Newton, haven't we?' I commented. 'I have read that he produced a monumental work of five volumes with the title *Treatise on Celestial Mechanics*. It is supposed to contain a detailed account of the dynamics of the solar system.'

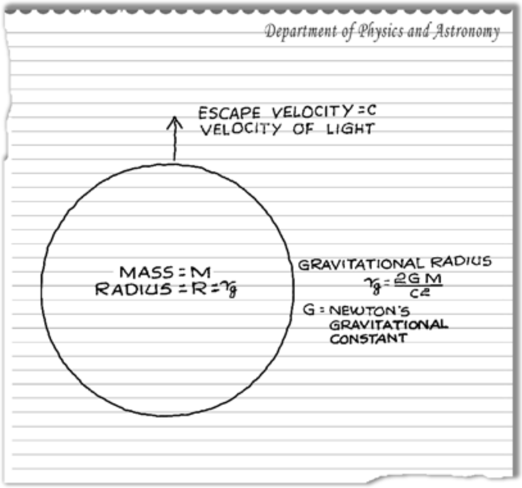
'That's right. Laplace also wrote a non-mathematical treatise, *Exposition of the System of the World*, which is considered to be a masterpiece. In this book he discussed the invisible stars. The principle is very simple. It is based on escape velocities.'

'Ah, escape velocity is something I know,' I told George and proceeded to air my knowledge. 'The escape velocity on the Earth for instance is the velocity with which you eject an object, say a rocket, so that it just escapes the gravitational pull of the Earth.'

'Do you remember the procedure to compute the escape velocity?' George asked.

'I learnt it a long time ago in school, George,' I answered. 'Let me see. Just equate the potential energy of the rocket on the surface of the Earth to its kinetic energy of ejection. The first is simply given by the product of the Newtonian gravitational constant and the masses of the Earth and the rocket, the whole thing divided by the radius of the Earth. And the kinetic energy is half the mass of the rocket multiplied by the square of the ejection velocity. Of course, when you equate the two, the mass of the rocket drops out.'

'Splendid. This way, equating the two energies, one can determine the escape velocity for any gravitating object be it the Earth or a star. Or equivalently one can express the radius of the central body in terms of its mass and the escape velocity. Of course, Newton's gravitational constant also appears in the formula. You follow?'



'Sure, everything is quite clear so far.'

'Now, here comes the twist. Let us ask the question: What if the escape velocity is equated to the velocity of light? Then light would just manage to escape the gravity of such a star. From the calculation you just outlined, we can find out the radius of such a star. It turns out to be twice the product of the gravitational constant and the mass of the star divided by the square of the speed of light. Let us call this quantity the gravitational radius of the star. Remember that. Light cannot escape from a star if its actual radius were to be equal to or smaller than its gravitational radius. Therefore it would be invisible to a distant observer, as Michell and Laplace conjectured. Simple, isn't it?'

'Yes, but I have a couple of doubts,' I said.

'Don't we all! Go ahead and fire away.'

'First, suppose I throw a stone with velocity less than the Earth's escape velocity. It may not escape from the Earth completely. Still, it will rise to a certain height and fall back. And I can thus hit a fruit on a tree with a stone. Likewise, in the case of this so-called invisible star, light *can* go up to a certain height if not escape to infinity. That means an observer within this range should be able to see this star. It follows that the star is not really invisible.'

'What is your next doubt?' asked George nodding. I knew very well that he liked to be questioned like this.

'Again just like a stone thrown up from the Earth, light from this invisible star must go up, slow down to a momentary halt and then fall back. Isn't this impossible for light? After all, we know that light must always travel at constant velocity.'

'Well, Alfie, they were not doubts at all,' George said with a smile. 'They were legitimate objections, Alfie. Objections to the Newtonian physics of this so-called invisible star. You must remember that the speculation goes way back before the advent of Maxwell's electromagnetic theory, let alone Einstein's special relativity. Laplace himself thought that the whole idea was so crazy that he dropped it from the later editions of his book. Nonetheless, the story leads to one of the strangest coincidences.'

'Which is?'

'I have to jump way ahead here. What we called the gravitational radius turns out to be exactly the radius of a non-rotating black hole!'

'You mean a black hole as we know it today within the framework of general relativity?' This was indeed a surprise.

'Precisely. This non-rotating or static black hole is contained in the spacetime discovered by Karl Schwarzschild,' announced George.

So we had arrived at the beginning of the saga of the real black hole.

In the course of my general reading on black holes, I had come across snatches of Schwarzschild's life and work. But I was eager to listen to what George had to tell me about this extraordinary personality.

'Well, Alfie, let me tell you a bit about the man whose work we are talking about. Karl Schwarzschild is considered to be one of the towering physical scientists of the twentieth century. The breadth and the range of his contributions are staggering, you know. They cover the entire range of physics, astronomy, and astrophysics of his time. In physics, for instance, Schwarzschild's work ranges from electrodynamics and geometrical optics to the atomic theory. Likewise, Schwarzschild's contributions to astronomy and astrophysics are many and varied. I won't even attempt to describe them. And, of course, the crowning glory of his career was his solution to Einstein's equations of general relativity. All of this in a brief twenty years, Alfie!'

George took a deep breath and continued.

'That is not all. Schwarzschild was a visionary far ahead of his time as well. He addressed himself to the question whether the geometry of the three-dimensional space of astronomy might be non-Euclidean. Not only that, he even made an estimate of its possible curvature. This was some fifteen years before the founding of general relativity. Can you imagine that, Alfie?'

'What did Einstein think of Schwarzschild's solution, George?' This was a natural question to ask.

'I knew you would ask that question, Alfie,' replied George. 'I am well equipped to answer that.'

George took out a page with some quotations on it from the bunch of sheets in front of him.

'Here it is. Einstein communicated Schwarzschild's paper, in which he had derived his solution, to the Berlin Academy on 13 January 1916. Amazingly enough, Schwarzschild did this work just about two months after Einstein had himself published the basic equations of his theory in a short communication. Einstein wrote on the ninth of January 1916: *I have read your paper with great interest. I had not expected that one could obtain the exact solution of the problem so simply. The analytical treatment of the problem appears to me to be splendid.*'

A distant, pensive look came upon George.

'All this was grand, Alfie,' he continued. 'But here comes the sad part of the story. The circumstances under which Schwarzschild derived his now famous solution were really heroic. During the spring and summer of 1915, he served in the German army at the eastern front with a small technical staff. At that time, Schwarzschild contracted pemphigus, a fatal disease. He died on the eleventh of May 1916. It was during this period of illness, literally on his deathbed, that Schwarzschild wrote his two papers on general relativity.'

It was a deeply touching story indeed.

'Let me tell you what Einstein had to say about this remarkable man,' George went on, picking up the page with quotations. 'On the twenty-ninth of June 1916, Einstein gave a brief memorial address on Karl Schwarzschild at a meeting of Berliner Akademie:

> *On May 11 of this year, Karl Schwarzschild, 42 years old, was by death snatched away. This early demise of so gifted and many-sided a scientist is a grievous loss not only to this body, but also to all his astronomer and physicist friends.*
>
> *…In his last year he became interested in the new theory of gravitation: he succeeded in obtaining, for the first time, an exact solution in the new theory of gravitation. And in the very last months of his life, much weakened by a fell disease, he yet succeeded in making some profound contributions to quantum theory.*

…Now bitter circumstances have taken him away: but his work will bear fruits and have an enduring influence on Science for which he devoted all his strength.'

'A heroic figure!' said George. I nodded my agreement in silence.

'Let us see what this spacetime of Schwarzschild's, outside a spherical mass distribution is all about. It is known as the Schwarzschild exterior spacetime,' George began and then paused a little before speaking. 'Alfie, before we started all this discussion of ours, you said you wanted to know about black holes in sufficient detail. Do you still want it that way?'

'Of course I do,' I said firmly.

'All right, we shall go slowly in describing the Schwarzschild spacetime. That is the only way to learn the true nature of the black hole. And it is not at all difficult, as you will see,' said George. 'When we met last time, we talked about the line elements both in flat and curved spacetimes, didn't we?'

'Oh, yes. In the flat spacetime, we have simply to add the squares of the spatial co-ordinate intervals and subtract the square of the time-distance between two events or the four dimensional spacetime points. Of course, we use Cartesian co-ordinates. Right?'

'Right. So the spatial squares are simply multiplied by unity and we attach a negative sign to the square of time-distance. Let us just say time, instead of time-distance, for simplicity. Now what happens in the case of the curved spacetime?'

'Well these squares of the co-ordinate intervals have to be multiplied by functions of spacetime co-ordinates just as, for instance, on the two-dimensional sphere. These are known as metric functions.'

'Excellent. The essence of the curved space, or equivalently the gravitational field it represents, is incorporated in these metric functions. How do we get them?'

'By solving Einstein's equations. There are ten equations. You get from them the ten metric functions that determine the geometry of the spacetime,' I repeated what I had learnt. 'You solve the equations making suitable, simplifying assumptions. And pray that the solution, if you find one at all, describe some physically meaningful gravitational field.'

'Well, I am not sure whether prayer would do any good, Alfie,' George chuckled. 'However, judicious groundwork in making your basic assumptions would go a long way in reaching your goal. Now let us see how we would go about finding the Schwarzschild exterior spacetime. Keep in mind that it should represent the gravitational field *outside* a spherical mass distribution. What would you say about the energy and momentum in this region?'

'I would guess that it is zero, since this region is empty,' I answered.

'Correct guess,' concurred George. 'Let us think of the properties of the gravitational field outside a spherical mass distribution as given by good old Newton. This should give us a handle on the nature of the all-important metric functions. Do you agree that the gravitational field is constant in time since the spherical mass, the source of gravitation, stays quietly at one place?'

'I agree.'

'Thank you. That means that our metric functions are also independent of time. We say that spacetime displays the property of time symmetry. Next, our friend Isaac Newton told us something very important about how the gravitational field outside a spherical mass behaves, didn't he?'

'He did indeed. The field acts as if the mass were concentrated at the centre,' I said. 'And it obeys the inverse square law.'

'That means the field depends only on the distance from the centre. Therefore, being quite clever, we select spherical polar coordinates with mass at the centre to describe our spacetime. You know these coordinates, I am sure.'

'Of course I do. In fact, we considered them last time, didn't we? We choose as our coordinates the distance from the centre, or the radial distance as it is called, and the angles corresponding to the latitude and longitude on any sphere drawn about the centre.'

'Right. On any such sphere, wherever you go, you will find the same gravitational field since every point on it is equidistant from the centre. This we call spherical symmetry. So what symmetries does our spacetime possess?'

'Time symmetry and spherical symmetry,' I answered.

'Splendid as always,' George had this habit of commending me with superlatives. Maybe he did the same thing to his students to boost up their morale. 'These spacetime symmetries, as they are called, are reflected by the metric functions, which are therefore independent of time and are functions of the radial distance alone.'

'Do these symmetries simplify metric functions?'

'Enormously. At the end of the day, you find that there are only four metric functions corresponding to the four coordinates. The part containing the angles is the same as for the flat spacetime. Quite trivial. And the metric functions for the time and radial coordinates turn out to be reciprocal to each other.'

'You mean you have just one function to solve in Einstein's equations then? I must say that *is* an enormous simplification.'

'That is the beauty of the Schwarzschild solution,' George said. 'Here comes something mind-blowing. This metric function is just unity for the flat spacetime, as you yourself told me. We have now introduced gravity due to a spherical mass distribution, haven't we? The change that occurs now in the metric is incredibly simple. Just a while ago we spoke about the gravitational radius, remember?'

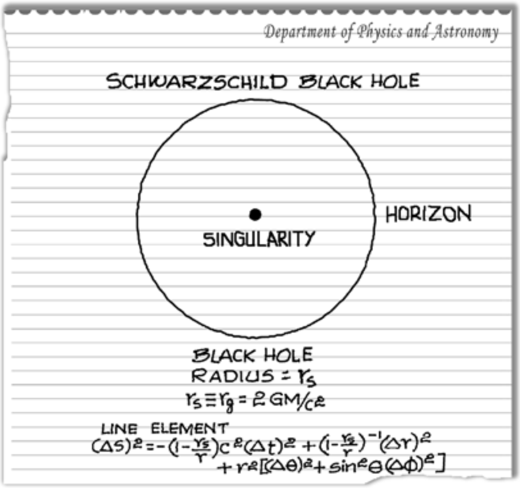
'Come on, George. My memory is not that short you know,' I protested. 'It is the radius of Laplace's invisible star. It is equivalent to twice the mass of the star divided by the square of the speed of light with, of course, the Newtonian gravitational constant multiplying it.'

'All right. Divide the gravitational radius by the radial distance of any point from the centre and subtract it from unity.'

'So?'

'So, that is just the metric function multiplying the square of the time interval with a negative sign in front of it. And the reciprocal of it without the negative sign multiplies the square of the radial distance.'

'That is it?'



'That is it,' George said with emphasis.

'That is what Schwarzschild discovered? That simple?' This was astonishing.

'Yes, that is what Schwarzschild discovered' George said exultantly. 'And, mark my word Alfie, this single function describes the entire spacetime geometry outside of a spherical source, be it a point mass or a spherical mass distribution or, what is important for us, the static, non-rotating black hole.'

This extraordinary simplicity emerging out of Einstein's complex equations was striking. But so was Newton's universal law of gravitation that accounted for the entire mechanism of celestial dynamics.

'I am sorry if I seem to be overly curious and jumping ahead,' I said apologetically. 'But where is the black hole hidden in this simple function describing the spacetime?'

'No problem, that is what I was coming to,' reassured George. 'We have just seen the exact expression for the metric function that goes along with the time.

Tell me at what value of the radial distance it becomes zero,' George leaned forward in expectation.

It took me hardly a moment to come up with the answer. 'My goodness, the metric function goes to zero exactly at the gravitational radius of Laplace where the escape velocity becomes the speed of light!'

'At the same time, that is where the metric multiplying the radial part of the spacetime interval goes to infinity too. And the spherical surface with the gravitational radius, my dear Alfie, marks the Schwarzschild black hole. This radius is also appropriately called the Schwarzschild radius. What a coincidence! Laplace merges into Schwarzschild.' George was practically beaming now, having led me in gentle, but precise, steps to where the black hole was.

'Alfie, my boy, we have reached our destination, the static Schwarzschild black hole,' George said. 'A sphere no less! We have come back to the Greek ideal of beauty and simplicity. This calls for a drink, don't you think? But no alcohol is allowed on campus, so just plain coffee.'

George got up, walked over to his cluttered table in the corner, and from what he called his organized disorder miraculously extricated a large, old fashioned, metal-clad thermos flask and two paper cups and brought them over.

'I hate the infernal coffee you get from vending machines, you know,' explained George, pouring the steaming liquid into the paper cups. 'So I bring my own brew.'

I tasted his brew, which had been mixed with the right amount of milk and sugar. It was wonderfully nice.

'I guess Schwarzschild did not live long enough to realize the implications of his discovery,' I said.

'Unfortunately not.'

'In any event, tell me, how was this novel feature of the spacetime received? I mean the fact that something unusual must happen at the gravitational radius. There must have been quite a bit of enthusiasm.'

'Enthusiasm? Hardly,' replied George. 'On the contrary, there was a general feeling of annoyance, abhorrence, and confusion. '

'But why?'

'Well, imagine yourself in the position of the physicists and mathematicians of the time, Alfie,' said George. 'Here is a spacetime in which the metric function associated with time goes to zero. Worse still, the one attached to the radial distance goes to infinity, blowing up in your face. This means the invariant length and the whole process of measurement beaks down on the Schwarzschild sphere. That is why this sphere was christened the *Schwarzschild singularity*. And no one likes a singularity, Alfie.'

'That seems serious all right. What about Einstein? How did he take this?' I was quite curious to know the reaction of the one who started the whole game.

'Einstein in particular did not like it at all,' answered George. 'Here was the man who had produced this magnificent theory of gravitation. He had expected that the curved spacetime would be smooth and free of pathologies just like the Minkowskian flat space. And now this mess! The simplest possible solution to his field equations, the analogue of Newtonian gravity of a point mass, goes haywire.'

'So what happened?'

'Well, among other things, a meeting was convened at the Collège de France in Paris in 1922 to discuss the status of relativity theory,' George recounted a piece of history. 'Believe it or not, some of the best brains were there at the meeting. The participants included the physicists Jean Becquerel, Henri Brilloin and Paul Langevin, and the mathematicians Eli Cartan and Jacques Hadamard, with the central position occupied by none other than Einstein himself. Hadamard raised the question of the Schwarzschild singularity, the ugly, unwanted child of the lovely spacetime. Becquerel called it a *Hole in Space*, a term close to our present day *Black Hole*. Eddington, who was not present at the meeting said it was the *Magic Circle* inside of which no measurement could bring us.'

'How about Einstein? What did he have to say?' I queried.

'Ah, let me see,' George selected a volume from his bookshelf, thumbed through it, and read out. 'Here it is. Einstein's reply to Hadamard was as follows: "If that term could actually vanish somewhere in the universe, it would be a true disaster for the theory; and it is very difficult to say *a priori* what could happen physically because the formula does not apply any more." Later, Einstein jokingly named the Schwarzschild singularity the *Hadamard Disaster*'

'Did Einstein come up with any kind of remedy for the situation at all?'

'Well, on the following day he came back with a calculation, which ostensibly ruled out the existence of the singularity. This was based on the exact solution Schwarzschild had derived for the interior of a sphere of matter with constant density that was supported by a suitable pressure. Suppose you try to compress this sphere. When the surface of the sphere reaches the value of nine eighths the Schwarzschild radius, the pressure at the centre would shoot up to infinity. So you cannot reach the Schwarzschild singularity on this model at all. But, of course, this is specific to the Schwarzschild interior, which is made of an incompressible fluid. It is not a general result.'

‘But, George, what was the final conclusion then?’ I asked.

‘At the end of their deliberations, sometimes the temperature rising above the normal level, the heavyweights failed to arrive at a satisfactory solution to the problem.’ George chuckled heartily at this unusual episode. ‘Of course, even Einstein did not understand what was happening. As I told you, Alfie, different people called the Schwarzschild surface by different names. We can call it *Einstein's Enigma*. It must have remained an enigma to the great man.’

‘That is a nice name, George. Did he worry about it further at all?’ I asked.

‘Sure he did, Alfie, he was not the type to let go of an unsolved problem.’ answered George.

‘So what did he do with this enigma of his?’

‘What would you do with something that bothers you? You try to get rid of it,’ said George. ‘You see, as late as nineteen thirty-nine, he wrote a paper on the subject. Let me show it to you.’

George took out the paper lying right on the top of the stack on the table and showed it to me. The title of the paper was *On A Stationary System With Spherical Symmetry Consisting of Many Gravitating Masses*. It had been published in the journal *Annals of Mathematics* and bore the date, October 1939.

‘Let me tell you briefly what Einstein does in this paper, Alfie,’ began George. ‘He considers a cluster of particles moving in circles about their common centre of gravity. Einstein says that this system resembles a spherical star system, or what we call a globular cluster.’

‘What is that?’ I asked.

‘Well, it is a cluster of stars numbering from, say, ten thousand to a hundred thousand, contained in a spherical volume,’ answered George. ‘Einstein considers this to be a good model for the spherical distribution of matter. As you can see, he carries out detailed calculations on the gravitational field of the system. If you keep reducing the radius of the spherical mass distribution, the particles have to move faster and faster to counter the gravitational pull towards the centre. Ultimately, when you reach the radius of one and half times the Schwarzschild radius, they will have to move with the speed of light to maintain balance. This is impossible we know. So Einstein's conclusion is that you can never attain the Schwarzschild radius in nature. Look at the final conclusion Einstein draws from his calculations.’

I read the last part of the paper:

> *The essential result of this investigation is a clear understanding as to why the “Schwarzschild singularities” do not exist in physical reality. Although the the-*

ory given here treats only clusters whose particles move along circular paths it does not seem to be subject to reasonable doubt that more general cases will have analogous results. The "Schwarzschild singularity" does not appear for the reason that matter cannot be concentrated arbitrarily. And this is due to the fact that otherwise the constituting particles would reach the velocity of light.

'So, what you termed as Einstein's Enigma may be called *Albert's Abhorrence* as well,' I said.

'True enough,' agreed George.

'Tell me something, George. Was there any flaw in Einstein's calculations?' It was not unimaginable, was it? Anybody could make a mistake.

'No, the calculations were correct,' George clarified. 'But Einstein did not take into account any radial motion of the particles. There lies the irony.'

'What do you mean the irony?'

'Well, in the same year, nineteen thirty-nine, Robert Oppenheimer and his student Hartland Snyder wrote a paper with the title *On Continued Gravitational Contraction*. They showed how a spherical ball of dust with no pressure acting would keep collapsing and fall through the Schwarzschild surface. This was a pioneering paper, which set the stage for all computations related to gravitational collapse. More than that, it demonstrated how the so-called Schwarzschild singularity could emerge out of the collapsing matter and become part of physical reality.'

'So, the Schwarzschild singularity could rear its head in the physical world. Then what do you do with this nasty singularity?' I asked. The situation seemed rather awkward, to put it mildly.

'It is neither nasty, nor is it a singularity, Alfie' assured George. 'It took decades after Schwarzschild's discovery of his solution to realize this fact in a completely satisfactory manner. The apparently pathological behaviour of this so-called singularity is due simply to the improper choice of coordinates. This can happen even in flat spacetime.'

'How is that?' This was unexpected.

'Suppose you choose spherical polar coordinates to describe the three-dimensional flat spacetime. A moment ago, you described these co-ordinates in connection with the Schwarzschild solution, didn't you? These co-ordinates involve trigonometric functions of the latitude angle as we discussed earlier. This angle is taken to be zero at the pole. And some trigonometric functions go to zero or even go to infinity at this point. But we know that there is nothing wrong with the pole. As a matter of fact, if you were to use Cartesian coordinates such singular behaviour does not even arise at any point of space, including the one you chose as the pole. And it is the same sort of thing with the Schwarzschild surface or the so-called Schwarzschild singularity, the improper choice of time and radial distance. The fault, dear Alfie, is not in our star, but in ourselves that we chose the wrong coordinates.'

'How now, dear Cassius, thou of lean and hungry look, where doth lie redress for this affair most singular?' I countered.

'I should have known better than to twist the Bard,' George slapped his forehead with his palm. 'Some people, including Eddington, tried to find co-ordinates in which there was no singular behaviour at the Schwarzschild radius. They met with partial success. It was only in nineteen-sixty that Martin Kruskal, a plasma physicist working at Princeton University, discovered new coordinates in which this apparent singularity did not exist. Also, George Szekeres in Australia discovered them independently. These coordinates are named after them.'

'So it took forty-five years to remedy the situation! Poor Einstein, he did not live to see his daemon finally exorcised. In any case, all is well with the Schwarzschild sphere then.'

'Yes, but a word of caution is in order,' warned George. 'At the origin, where the radial distance is zero, there is a real singularity which cannot be removed by any means known to man or beast.'

'What happens there?'

'Spacetime curvature becomes infinite at that point and Einstein's equations break down. We shall talk about it a bit later on.'

'All right. But, how did the physicists bear to live with what they thought was a singularity at the Schwarzschild sphere during all those years before it was shown to be innocuous?'

'Simple, Alfie. They convinced themselves that this annoying monstrosity does not exist in nature. Even if you cannot *prove* that it cannot. Let me explain. If you compute the Schwarzschild radius for the Sun, for instance, it turns out to be a mere 3 kilometres, which is well within the Sun's interior. In the case of the Earth it is just about a centimetre. And for a person weighing 100 kilograms, the Schwarzschild radius in centimetres is approximately one divided by a huge number, namely one followed by 23 zeroes!'

'Don't tell me that deep within me I carry a miniscule black hole!'

'A black heart maybe, but definitely not a black hole,' George shrugged. 'You see, the peculiar behaviour at the Schwarzschild radius occurs only in empty space. If it is covered with matter, nothing unusual happens there. This was borne out by the exact solution Schwarzschild derived for the interior of a spherical mass distribution of constant density. We talked about this solution a while ago.'

'Do I understand then that when the sphere of Schwarzschild radius exists in empty space, then and only then, you are faced with the problem of a singularity as it was considered?'

'That is right. If the Sun were to exist as a star with radius of only three kilometres, then its density would be nearly a billion billion grams per cubic centimetre. This was an unimaginably high density. The possible existence of such stars confined within the Schwarzschild radius was ruled out. So the physicists of the time could stop worrying about the Schwarzschild surface being part of physical reality, and creating problems they did not understand.'

'But now we know that a star can collapse through the Schwarzschild radius and we are inevitably left with a black hole.'

'That is perfectly correct, as was demonstrated for the first time by Oppenheimer and Snyder,' averred George. 'So let us assume that the star has collapsed, the Schwarzschild sphere is out in empty space, a black hole has formed with all its strange properties. That is what we shall explore presently.'

George thought for a moment and picked up another photocopied sheet from the stack on the table.

'Alfie, here is a short note by the eminent physicist Freeman Dyson entitled *Every Genius Has A Blind Spot.* As always, you may keep it, but let me read a few sentences that should interest you.'

> *We know, fifty years after the death of Einstein that black holes are abundant in the universe and play an essential part in its evolution…For us, black holes are the most beautiful and spectacular confirmation of Einstein's theory of general relativity. They are the places where Einstein's theory shows in full power and glory. And yet, Einstein himself did not believe in black holes. He was not even interested in examining evidence that they might really exist. Einstein's lack of interest in black holes remains one of the enduring mysteries in the life of a genius.*

'Well, George, looks like the black hole was not only an enigma to Einstein, but his lack of interest in them is an enigma for us too,' I remarked.

'That is indeed the situation, Alfie,' concurred George.

The telephone on George's desk rang, startling us momentarily as we were deeply engrossed in our discussion.

'Oh, I guess I have to answer the phone,' said George. 'Just as well, we needed a short break, I think. Make yourself comfortable, Alfie. We shall get back to the black hole shortly.' He went over to take the call.

My thoughts drifted back to Schwarzschild. He must have been a remarkable person. Out of the complexity of Einstein's equations he had conjured up the simplest and yet one of the most important spacetimes. But what a tragedy! The first solution Schwarzschild had discovered happened to be his last statement as well.

Chapter 12

SPHERE OF DARKNESS

George came back after answering the phone call. 'Well, there is a faculty meeting tomorrow and the Chairman of the department can't make it,' he told me. 'So, he wants me to chair the meeting. The onus of seniority, you know. I can't say no, *noblesse oblige* and all that. Feynman apparently refused to serve on any university committees. Maybe he never attended any meetings either. But we cannot all be Feynmans, can we?'

George poured some more coffee into our empty cups and took a couple of sips before launching upon the central theme of his exposition.

'Ah, back to the black holes,' George seemed to be quite eager to continue our discussion. 'Let us first define what we mean by a black hole.'

'That is what Voltaire used to say, it seems, define your terms before you discuss them. In other words, definition before discussion!'

'Good idea. Some people refer to the Schwarzschild surface itself as the black hole. The surface is called the *event horizon*. We shall soon see why in detail. Others consider the surface as well as the space within it including the singularity at the centre as the black hole. Let us not worry about these subtleties. The context will tell us what we mean by the black hole.'

'George, you didn't define your terms at all. You fuzzed them,' I objected.

'That is called fuzzy logic, Alfie,' shrugged George. 'Now, let us get down to some real basics, something often glossed over.'

'That would be nice, George,' I said. 'I would like to understand what the black hole really is.'

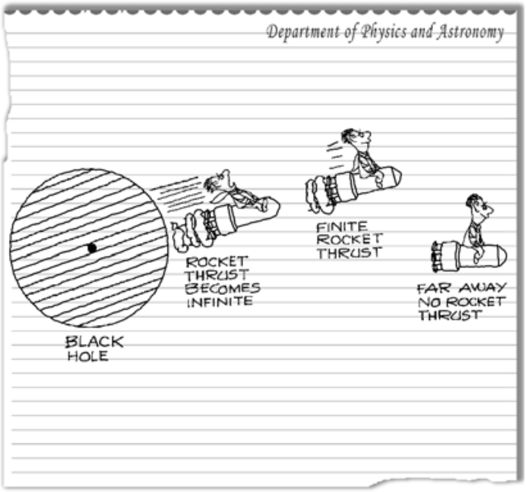
'Good. The Schwarzschild black hole, or the event horizon, is characterized by three properties. Let me enumerate them. First, it is a *static limit*. Second, it is an *infinite redshift surface*. Third, and most important, it is a *one-way membrane*. Remember these three cardinal characteristics of the black hole, Alfie. We shall see what each one of them means.'

'I shall remember them, George,' I said. 'And as you explain them, these concepts and properties will become clear.'

'Let us start with the idea of being static in a gravitational field. A natural property of the Schwarzschild spacetime is that at large distances from the source of gravitation, it becomes flat as the gravitational field dies down.'

'Like the curved net of the fallen acrobat,' I said.

'Ah, you remember the cartoon I showed you,' said George happily. 'In the flat regions of space, where no force is acting, we can have static, unmoving particles everywhere. Each of them can stay put, floating blissfully at one fixed point. By particles we include material objects, observers, sources of radiation and what not. Let us see what happens if we journey towards the black hole. As we inch towards it, the inward gravitational pull starts acting. Gravitational tug exists on the surface of the Earth too, right? But we can sit here merrily, because the solid Earth supports us. It is the electromagnetic forces among the atoms that imparts this resistance to the solid.'



'In other words, as Richard Feynman says somewhere, gravity pulls you down and electromagnetism holds you up,' I interjected.

'Ah, expressed in the typical Feynman style! On the other hand, if you want to be static in empty space above the Earth, you need a little rocket to sit on, whose thrust counters the gravitational attraction towards the centre.'

'So each of us should be equipped with a custom made rocket to sit upon and chat in outer space. That would be fun.'

'Initially, yes,' said George. 'But as you move towards the black hole, the gravitational pull keeps increasing steadily. The thrust of your rocket too has to keep going up. When you reach the black-hole surface, the gravitational force, and consequently the thrust needed to keep you static, shoots up to an infinite value.'

'Sorry to interrupt you, George,' I said. 'The Newtonian gravitational force due to a point mass also keeps going up as the radial distance from the centre is reduced. But it will go to infinity only when you reach the centre or, in other words, when the radial distance becomes zero. How come gravity becomes infinite at the black hole surface itself in the Schwarzschild spacetime?'

'A very perceptive question, I must admit, Alfie' nodded George. 'Well, suppose you compute the gravitational force acting on a static observer in the Schwarzschild spacetime using the formalism of general relativity. Believe me, it is quite a simple calculation. Then the result you get is nothing but the Newtonian gravitational force divided by the metric function that goes with time in the Schwarzschild line element. This makes a world of difference, doesn't it? Of course, far away form the black hole, Newton and Einstein give nearly the same value for the gravitational pull. But when you approach the black hole, the general relativistic effect becomes predominant. And when we approach the black hole surface, the gravitational force becomes infinite, since the metric function in the denominator goes to zero. Is it clear now?'

'Absolutely,' I said. 'Now I understand why the rocket thrust required to keep the observer static goes to infinity at the black hole surface.'

'That is fine,' continued George. 'In other words, no rocket can ever overcome the gravitational pull. Consequently, you cannot remain static when you reach the black hole.'

'Aha, that is why the black hole is called the static limit?'

'Exactly. We have looked at this property from a physical angle, that too in a qualitative manner. Let us consider the static observers from the spacetime point of view.'

'In a manner Einstein would have approved,' I remarked.

'Right you are, Alfie, since it would have taken the mystery out of the black hole. What I am going to tell you will be a little bit more technical than rockets and their thrusts. Are you ready?'

'Sure, George, go on,' I assured George.

'Last time we met at Bruno's, we talked about the world-line traced by a static observer, remember?'

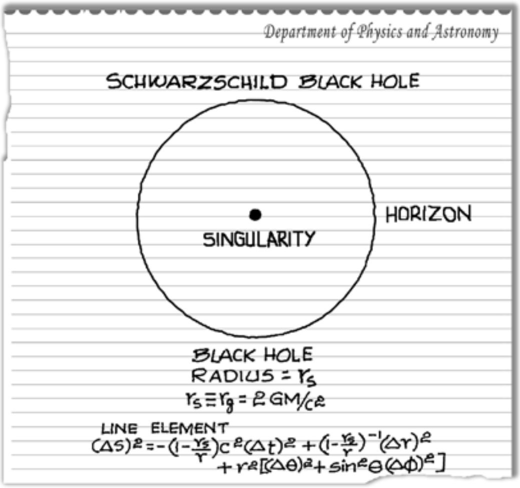
'Oh, yes. Since the spatial position of the observer is fixed and only time changes, the world line just follows the direction of time.'

'That is right. And his time measure has to be normal, without any pathological behaviour, if the static observer can be defined at all. This is so until we reach the Schwarzschild surface.'

'Then the time measure goes to zero and the radial part becomes infinite.'

'Exactly. So the black hole surface signals the end of having a static observer whose world-line has to follow the time direction. Get it?'

'Yes, indeed,' I said. 'But I have a question.'



'What might that be?'

'How does the spacetime picture change if we enter the black hole?'

'Aha, I should have known that question was coming,' remarked George. 'Alfie, can you pull out the diagram of the Schwarzschild black hole we drew with the spacetime line element? Ah, there you are! Let us figure out the situation now. The metric function of time becomes zero on the black hole surface and then changes sign when we cross it. And the sign of the one that goes with the radial distance reverses too, when we cross over to the interior of the surface.'

'Are you telling me that time becomes like space and the radial direction looks like time?

'Indeed that is the implication of the change of signs.'

'Don't tell me, that when I enter the black hole, my watch changes into a measuring rod and my ruler is transformed into a clock!'

'You have a weird imagination, Alfie,' George laughed. 'Once again the change in the nature of time and space measures is due to our choice of inadequate coordinates. In the Kruskal-Szekeres coordinates this does not happen. There the new co-ordinates are combinations of time and the radial distance.'

'All right, I shall take your word for it,' I told George. 'But tell me, if you cannot have static observers within the black hole surface, what kind of observers *can* you have?'

'Oh, well, the irrepressible power of gravity takes over within the black hole. All particles, including our observers, will have no choice but to keep falling.'

'Free fall and no free will!'

'Well, that is as far as the observer in free fall is concerned.'

'What will eventually happen to the unfortunate observer – or any kind of matter – who falls into the black hole then?'

'Well, anything and everything entering the black hole will hit the singularity and will become part of the matter that has already collapsed. We shall come back to this later on.'

'Well, I should have known the fate that awaits all who enter the black hole.'

'Now that we have seen how the black hole is characterized as the static limit, let us find out why it is called the infinite redshift surface,' said George. 'Some more coffee?'

'Just a little. Let me do the honours.'

I poured some coffee into the cups. It was quite satisfying to sip something hot and pleasant while talking.

'Redshift then,' resumed George. 'Hark back to our last discussion, Alfie. We learnt how Einstein deduced the gravitational red shift from his equivalence principle.'

'Oh, yes. We had a source of radiation fixed on the floor of a rocket accelerating upwards and an identical receiver at the top. Waves got stretched by the time they reached the receiver, as they had to cover increasing spatial intervals, giving rise to the redshift. By the equivalence principle, it was argued, that this should happen in a gravitational field as well. You also told me that this was a Newtonian approximation, which would be suitable only for weak gravitational fields.'

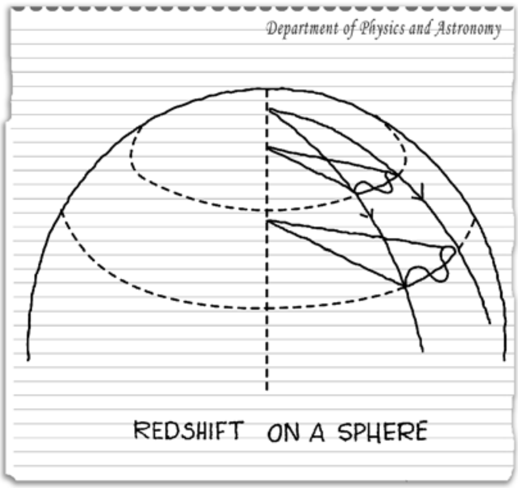
'True. Nevertheless, the ideas Einstein developed are still valid. Like identical clocks at different locations, waves emitted that have their frequency locked on to the clocks and so on. But now, we have to take a spacetime approach and get the exact general relativistic formula.'

'The idea of static limit was quite simple. How about the spacetime picture of redshift, George?'

'That is quite simple too. And so is the slowing down of clocks in strong gravitational fields, which goes hand in hand with the redshift. Let me illustrate it by a two-dimensional spatial analogy. You know what surface we have in mind?'

'Going by precedents, I would say we are going to land on the sphere again.'

'Easy guess!' smiled George. 'On the surface of the sphere, take two longitudinal lines. Draw two latitudes between these two longitudinal lines. Let us say that the one nearer to the pole corresponds to the source of light and the other to the observer. Suppose the source is switched on and off. Let it emit a wave train that spans the latitudinal segment between the two longitudinal lines. The wave train has, say, three extremes, two crests with a trough in between. Assume that this corresponds to three centimetres along the latitude. We may think of these three centimetres as three ticks of the clock at the source. Now, let this wave train, with end points on the longitudinal lines, move towards the observer. Do you see what happens?'



'Oh, yes. The number of extreme values remains the same. They cannot be changed in transit. But the wave train has been stretched out.'

'The distance between the crests, which measures the wavelength, has increased. What do you call it?'

'Redshift, of course!'

'Right. Now, let the observer measure lengths with a ruler identical to the one at the source. So he finds the length of the wave train to be, say, six centimetres. Let us assume that the centimetres correspond to the ticks of the clocks, as would be the case when dealing with the real spacetime situation, rather than the present two-dimensional spatial analogy. Then what the source measures as three ticks for the transit of the wave train, the observer sees as six. In other words, the clock at the source is running slow compared with that of the observer. Alfie, don't forget, all this is coming out of the curved space.'

'That is really nice, George.' I liked it a lot.

'Now, take the ratio of the wavelength measured by the observer to that at the source. It gives you the redshift. What we have is just the ratio of the distances along the two latitudes. But, this distance is nothing but the length of the segment of the latitude circle between the two longitudes. Therefore, it is proportional to the radius of the latitude circle. What is it called?'

'What do you know! It is the metric on the sphere. Or its square root, since the metric refers to the square of the lengths.'

'Bull's-eye, Alfie! The redshift is given by the ratio of the square root of the metric function at each of the two points. As we discussed earlier, this function depends on the radius of the sphere and the latitude angle in a very simple manner. Watch what happens now,' George was warming up. 'If we move the source closer to the pole, the metric function keeps diminishing and so does the separation along the latitude. What happens to the redshift then?'

'It keeps increasing obviously.'

'And as we approach the pole the redshift tends to infinity!'

'Are you telling me that all this takes place in the Schwarzschild spacetime?' The two-dimensional analogy was simple yet revealing. Even the mathematics involved was easy to grasp.

'Yes, Alfie, yes,' George affirmed exuberantly. 'The calculation is very simple. And the result you get is exactly the same. The redshift is the ratio of the square root of the metric associated with time at the observer to that at the source. So, as the source is placed nearer and nearer to the black hole surface, the redshift keeps increasing, tending to an infinite value in the limit.'

'What does infinite redshift mean?'

'It means that the observed wavelength may go way beyond anything we normally observe, beyond the visible, beyond radio waves. In fact, you can say the emitted radiation is not observed at all.'

'Now I understand why you said the black hole is an infinite red-shift surface,' I said. 'As usual, I have a question for you. Let us get back to the slowing down of clocks in a strong gravitational field. Does a person living in such a field realize that his clock is running slow?'

'No way!' answered George. 'All natural phenomena occur at a rate that matches the passage of such a person's own time – his proper time – from atomic processes to biological changes. Your heartbeats, for example, won't tell you that your clock is running slower compared with that of your friend sitting far away in a weaker gravitational field. Galileo would measure the same pulse rate whether he is perched on the top of the tower of Pisa or standing in the cathedral on the ground next to the tower.'

'You know, George, heart beats, gravity and longevity are strangely interconnected,' I mentioned something I had read long ago.

'Really, how is that?' George asked with interest.

'You see, the heart of every mammal beats some 800 million times in its lifetime. Consequently, longevity depends on the rate of heartbeats. As a matter of fact, the lighter the mammal in question is, the faster are its heartbeats and therefore the shorter its life. For instance, the heart of a mouse weighing 30 grams beats some 600 times a minute, and it lives for a mere 3 years. A 50 ton elephant with a heart beat rate of 30 per minute has a life span of around 40 years.'

'That is interesting,' remarked George. 'Let me see, we humans, with our hearts pounding away 60 to 70 times per minutes are given only 20 to 25 years to live except that modern medicine prolongs our lives. In any event, the moral of all this is that the heavier you are, the longer you should live. I knew it all the time.'

'All right, coming back to the gravitational time dilation, is there really no way that the guy in strong gravity can find out that his clock is running slow?'

'No, not unless he compares his clock with the one in a weaker field,' answered George. 'There are two ways of doing it. First, having lived in strong gravity for some time, he can visit his distant relatives. He will find that they have aged much more than him, since their clocks go faster than his.'

'Wait a minute, this is just like the twin paradox! Isn't it, George?' There seemed to be a parallel between the two phenomena.

'Of course it is, Alfie' George explained. 'When the astronaut twin accelerates or decelerates he is, in fact, experiencing the effects of a strong enough gravitational field according to the equivalence principle. So his clock must slow down, and he should age less than his stick-in-the-mud twin who refuses to leave the weak gravity of the Earth.'

'Everything seems to fall into its rightful place,' I remarked. This was quite pretty.

'That is the beauty of a well-constructed theory, Alfie,' responded George.

'Now, you said there were two ways a person in strong gravity can find out that his clock is running slow,' I reminded George. 'What is the second method?'

'Well, through the redshift, which we have just discussed,' answered George. 'The person in strong gravity sends a wave train of blue light to the distant observer. He also sends a message conveying information about the colour and the duration of the wave train. His distant friend receives the wave train redshifted to, say, yellow, for a longer duration as measured by his own time. From this he can tell how slow the strong gravity man's clock is running, and can then transmit this information back to the other man.'

'Or the whole process can be reversed, with the strong gravity man receiving blueshifted light from the distant observer and figuring out how slow his clock happens to be running, am I right?'

'That is correct. Now let us get back to the black hole. As we have seen, time goes progressively slower as we approach it. For instance, let our distant observer record, say, ten ticks of the clock, which he measures as ten seconds. For an observer sitting at a distance of four-thirds the radius of the black hole surface those ten ticks would correspond to five seconds of his proper time. Similarly, at a distance of one-and-one-hundredth of the black hole radius the distant ten ticks are equivalent to about one second, at one-and-one-millionth of the radius just one thousandth of a second and so on.'

George paused for a moment before reaching the natural culmination of this process. 'And finally, when we reach the black hole, the elapsed proper time of the static observer tends to zero as compared to that of the far-off observer. Time stands still. The distant clock may tick away forever and ever, but time in the strong gravitational field seems to have stopped flowing. We have now arrived at the black hole.'

'A dimple on the cheek of eternity,' I said quietly.

George looked up in surprise and asked, 'What did you say?'

'The black hole is a dimple on the cheek of eternity,' I repeated.

'That is a lovely description of the black hole, Alfie,' said George.

'Not really original, I must confess,' I said. 'You know about Taj Mahal in India I am sure.'

'Who doesn't? Supposed to be the most exquisite edifice in marble.'

'Yes, it was built by the Emperor Shah Jahan in the seventeenth century as a monument to his love for his queen Mumtaz Mahal who died giving birth to a child. The celebrated Indian poet Rabindranath Tagore is said to have described Taj Mahal as a teardrop on the cheek of eternity. Sad but beautiful!'

'Yes, it is, Alfie.'

George sat back in his chair and fell into a spell of meditative silence. He must have been thinking about the properties of black holes that he had already explained, and musing over what he was going to say about their other aspects. George had worked for decades on black holes. I am certain that he found in them not the mysterious and elusive entities of popular imagination, but very real objects of rare beauty.

'All right, Alfie, we have learnt that the Schwarzschild black hole is the static limit and an infinite redshift surface,' George resumed his explanation. 'But do they make it a black hole? No, sir! But, we are now ready to consider the third and the definitive characteristic of the black hole.'

'Ah, the one-way membrane property you mentioned,' I recalled.

'Precisely. We would like to know what makes the black hole a one-way membrane, why things can fall into it but cannot come out. Almost all books and all articles describe this phenomenon in the same manner, a *mantra* so to speak, you know that?'

'Indeed I do. *The gravitational pull of the black hole is so strong that nothing, not even light, can escape from it*,' I repeated the universal description of the black hole.

'That sounds almost like a tautology to me,' George remarked. 'Why doesn't light escape? Because gravity is so strong! How strong is gravity? Strong enough to hold back light!'

'What you said just now reminds me of the definition of gravitation according to Ambrose Bierce,' I said.

'You have a quotation for every occasion up your sleeve, don't you?' George was amused.

'Let me tell you how Ambrose Bierce defines gravitation in his *Devil's Dictionary*. *Gravitation: The tendency of all bodies to approach one another with a* *strength proportioned to the quantity of matter they contain – the quantity of matter they contain being ascertained by the strength of their tendency to approach one another. This is a lovely and edifying illustration of how science, having made A the proof of B, makes B the proof of A.'*

George laughed heartily. 'Well, the situation is not that bad, Alfie. First of all, nobody denies that the gravitational field of a black hole is strong. That is why it belongs to the general-relativistic regime.'

'I understand. Just a while ago, you explained how the gravitational pull becomes infinite at the black hole,' I said.

'But, remember that it is the pull experienced specifically by the static observer at the black hole,' pointed out George. 'All that it is saying is that you need infinite thrust to counteract this pull. Or, in other words, that a static observer cannot exist right at the black hole's surface. Let us try another approach to the question of the strength of the gravitational effects at the black hole's surface.'

'You mean an alternative indicator of the strength of the gravitational effects of the black hole?'

'Exactly. In general relativity, spacetime curvature is the essence of the gravitational field. So, let us think of the spacetime curvature at the event horizon.'

'Does the curvature manifest itself in any physical effects?'

'You bet,' smiled George. 'Tidal forces are directly related to the curvature. Remember the discussion we had when we met at Bruno's? In a freely falling frame, you can get rid of gravity, but you are still stuck with the tidal force. Therefore, it is the surest indicator of the gravitational effects in spacetime. Now, the curvature of the Schwarzschild spacetime goes as the mass divided by the cube of the radial distance. And, accordingly, so does the tidal force. You can compute this for any spherical mass-distribution at any radius in the corresponding Schwarzschild spacetime.'

George paused before continuing. I felt that he was about to tell me something important.

'Now, here comes the surprise, Alfie,' George spoke up. 'Take a neutron star of one solar mass, whose radius is about ten kilometres. Compute the spacetime curvature, or equivalently, the tidal force at its surface. You can easily show that this is larger than the tidal force you would encounter at the event horizon of a black hole of a little over five solar masses, which naturally has a radius of about fifteen kilometres. Such black holes are very common indeed. And the higher the mass of the black hole, the smaller the tidal force at its horizon.'

'George, this is really counter-intuitive,' I said. Yes, it was a surprise all right.

'That is not all. Take a white dwarf of one solar mass. It is about the size of the Earth, roughly six thousand four hundred kilometres in radius. The tidal force at its surface would be greater than that at the event horizon of a black hole of about a hundred thousand solar masses and above. As we shall see, supermassive black holes of millions to billions of solar masses exist at the centres of almost all galaxies including our own Milky Way. The tidal forces at their horizons would be much smaller than that at the surface of a white dwarf.'

'Let me try to summarize what you have told me,' I said. I wanted to be certain that I had understood George's arguments. 'The gravitational force on a static observer goes to infinity at the black hole, but it is specific to such observers and shows that they cannot exist once you reach the black hole's surface. If you consider freely falling observers, on the other hand, the gravitational tidal effects of the black holes can even be smaller than those of neutron stars and white dwarfs, depending on the mass of the black hole concerned. Therefore, we come to the conclusion that to say the gravity of the black hole is strong is not a very meaningful and precise statement!'

'Looks like it, doesn't it?' said George. 'This is certainly true when trying to understand the nature of the horizon. Moreover, the so-called strength of the gravitational field at the black hole does not in any way explain its one-way-membrane behaviour.'

George paused for a moment before continuing. 'Now, let us look at another myth before we try to understand the defining property of the horizon. You must have come across the statement that the black hole is so dense that it does not allow light or anything else to escape. Haven't you?'

'Oh, yes, I have,' I affirmed.

'Now how do we define the density of a black hole? A black hole is not a material object. Its surface is just that, a surface in space devoid of material content. And the space it contains is empty except for the matter that has collapsed to the centre. Therefore the density of a black hole is not a well-defined concept at all. If you wish, you could divide the mass of black hole by the volume of a sphere of Schwarzschild radius and call it the density. You end up with a huge number for a solar-mass black hole. But this does not work for super-massive black holes you know. In fact, this was realized as far back as 1920, when Sir Oliver Lodge, the physicist, speculated upon the possibility of having a black hole made up of some million billion Suns with a density of around a million-billionth of that of water. Is this the high density of a black hole one talks about? In any event, this so-called density of the black hole doesn't tell you why things can fall in but cannot come out.'

'How about the mass that has collapsed? Can one define its density directly?'

'Well, you are poking the monster now. From the point of view of classical physics, the mass has collapsed to a point, which by definition has zero volume. Which means, irrespective of the value of the mass, the density is infinite. This doesn't help. Again, it doesn't say anything about the one-way property of the event horizon. Speaking of the matter that has fallen in, it has been conjectured that quantum effects can be expected to stop the collapse before the mass hits the centre.'

'Does that mean that the mass now occupies a definite, non-zero volume?'

'Alfie, here we are in the realm of pure speculation. Quantum effects are supposed to come into play at extremely small distances. How small? Take the number one followed by 33 zeroes which is a billion trillion trillion. Divide unity by this number. At such inconceivably small distances the quantum effects related to gravity are supposed to raise their heads. So if the collapse were to be stopped by some all-powerful quantum mechanic, it would be at a radius of this order. I shall let you try to imagine in vain how small the corresponding volume would be and how high the density of this object, or whatever you may call it, might be. It makes no sense, if you ask me. The bottom line is that we can't meaningfully talk about the density of a black hole, let alone connect it with the trapping of light.'

'You pointed out to me just now that you can pick a black hole of suitable mass such that its gravity, as indicated by the tidal force, is comparable to that of a neutron star. But the two behave so differently. How is that?'

'Good question, Alfie. Let me illustrate the difference by an analogy,' George elucidated. 'Take a bowl, which represents the effect of gravitational attraction. Place a ball at the centre. This is our neutron star. If you pour water, it will flow down the bowl, hit the surface of the ball and splash back. Now replace the bowl and the ball by a sink. This simulates the black hole. Pour water into the sink and it will simply go down the drain.'

'Ah, I see the difference, George,' I said. 'A neutron star is a material object, whereas a black hole is purely a spacetime phenomenon. The curved spacetime somehow contrives to create an enclosure with no exit.'

'You got it, Alfie,' remarked George. 'Let us see how spacetime creates this enclosure with no exit, marked by a surface which acts as a one-way membrane, as it is called.'

George regarded me for a moment with an almost mischievous smile and then said, 'You know, Alfie, even here on the Earth, our spacetime is inhabited by countless one-way membranes.'

'What, don't tell me we are surrounded by a host of black holes,' I said incredulously.

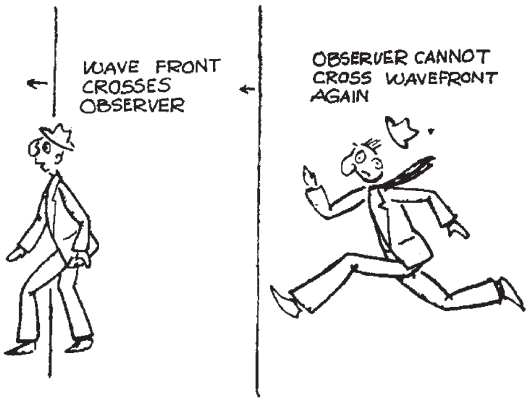
'Did I mention black holes?' retorted George. 'Every moment of your life you are entering one-way membranes that you will never be able to re-cross. In fact you wouldn't be able to live without them.'

'Please, George, stop being so enigmatic. Where are these mysterious membranes of yours?' I asked.

'Wave fronts, Alfie, wave fronts!' George grinned with amusement. 'We have already discussed them when we had that marathon session on relativity theory at Bruno's last time, haven't we? Let me recapitulate. You know light travels as wave fronts. A point source of light gives off spherical wave fronts that expand with the speed of light. Far away from the source they can be considered to be plane surfaces. Whatever their shape, you see light whenever these wave fronts hit you. When such a wave front passes you in a specific direction, you are in effect crossing it, or entering it so to speak, in the opposite direction. Do you agree?'

'Agreed.'

'If you want to re-cross it, how would you go about it?'



'Oh, yes, we talked about this. I would turn around and run like mad to catch up with it.'

'Aha, trying to be a modern-day teenage Einstein, are we? Is it possible?'

'No way! To achieve this I would have to run faster than light. This is simply impossible. Einstein told us so.'

'Do you see what is happening? You crossed the wave front, you fell through it. But you cannot re-cross it, you can not come out of it. Therefore every wave front acts as a one-way membrane. Simple as that!'

There was nothing new in all this. In fact, we had discussed this phenomenon in detail. Yet, the angle from which George had analysed it now was refreshingly novel.

'This is quite interesting, George,' I said. 'But, tell me, how is this relevant to the idea of a black hole? After all, the wave front travels with the speed of light and expands out, whereas the black hole surface does not move at all.'

'Let me first give you a very qualitative account of how the two phenomena are closely related,' answered George. 'Then, if you like, we shall work out some details which may give more insight.'

I nodded eagerly.

'We have seen how a wave front acts as a one-way membrane. This is purely a geometrical property, nothing to do with the electromagnetic phenomenon associated with the wave front. So, suppose you strip the wave front of the electromagnetic field it carries. We can still think of a surface in spacetime, not made of any material, a purely geometric entity, which retains all the properties of the wave front and travels with the speed of light. In other words, you have a geometric surface travelling with the speed of light, which acts as a one-way membrane. Now unleash gravity. As we have seen, it can slow down the propagation of electromagnetic waves. Which means gravity can slow down a wave front, or our geometric surface. If the gravitational force is increased steadily, as when you move towards the gravitating source, there comes a critical point when gravity can hold this geometric surface fixed in space. You may cross it in one direction and go in, but can never re-cross it and come out, just as it happened to you in the case of a travelling wave front. This, my dear Alfie, is the black hole or the event horizon! In short, a black hole is nothing but a wave front, shorn of its electromagnetism but retaining its geometric properties, held in position by gravity, and frozen in space and time. This is not a mere metaphorical description, Alfie, but a mathematical fact. Nothing can emerge out of the horizon as a result. No information about any event occurring within it can be received by observers stationed outside. It is therefore called the event horizon. Now you know the true essence of a black hole.'

George sat back to rest awhile. So this was the crucial, defining property of a black hole. There was no need to talk about the strength of the gravitational field or the density of the black hole. Even though I was yet to learn in more detail about this phenomenon, which is fundamental to a black hole, it was already obvious how essential it was to the spacetime structure of the event horizon.

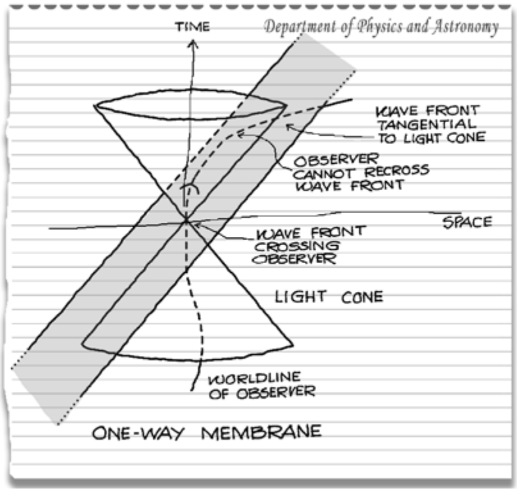
'As always, let me try to sum up what I have learnt about the defining property of a black hole, George. A layman's understanding, you know,' I said. 'A black hole is a region of spacetime, enclosed by a closed one-way membrane created by the spacetime curvature, into which material particles and light can enter but cannot come out. Am I right?'

'Ah, the man wants to have the last word on everything,' George nodded with his ready smile. 'You are perfectly right, Alfie.'

George mopped his brows with his handkerchief. I was sure that he had talked about his favourite subject any number of times. Still it excited him, and in all probability exhausted him, as though he had just discovered the effect he was explaining for the first time.

'Are you satisfied with what you have heard or should we go on to some more details of the unusual phenomenon?' George asked.

'If you are ready to go on, I am with you,' I answered.



'Very well, then. The magic is performed with light cones,' George illustrated his explanation slowly so that I could follow the details. The drawing was more or less the same as George had drawn while discussing relativity theory when we had met at Bruno's. 'Let us, as always, go back to flat spacetime. Here is a surface, which is tangential to the light cone. Every point of this surface moves with the speed of light. What does it represent?'

'Let me see, a wave front of course,' I answered after a moment of thought.

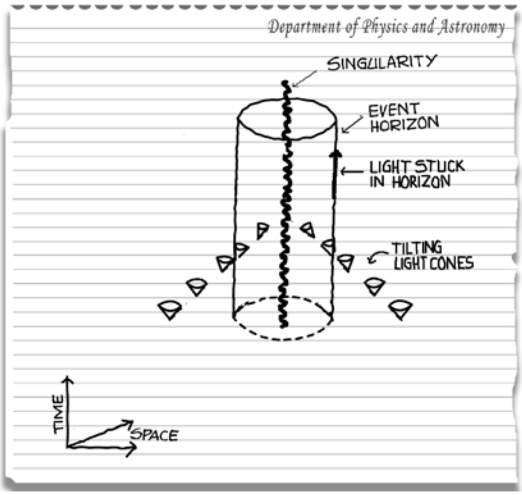
'Precisely. As we saw last time, the world line of an observer can never cross the light cone since he cannot travel faster than light. Equivalently, he can cross the wave front in one direction, but cannot re-cross it in the opposite direction.'

'That clearly demonstrates the one- way membrane property, I must admit.'

'Whenever a surface in spacetime, not necessarily a wave front travelling with the speed of light, is tangential to the light cone this happens.'

'So the event horizon is tangential to the light cone. Is that what happens in the case of the Schwarzschild spacetime then?'

'That is correct, Alfie. Here, of course, the event horizon is fixed in space, but the light cone tilts to become tangential to it. Let me show you how the light-cone structure evolves as we move from the far regions of space towards the black hole. The event horizon, which is a sphere, is represented by a circle drawn out in time. So it looks like a cylinder with time as its axis. In the flat



regions, we know how the light cone is. If light is emitted from a source, light will travel in both the outward and inward directions with respect to the black hole. As we travel towards the black hole, the cone tilts more and more towards the black hole. Finally when we reach the event horizon, the cone becomes tangential to it. If light is emitted here, the inward ray enters the event horizon and travels on ultimately to hit the singularity. What was supposed to be the outgoing part of the wave is stuck in the event horizon.'

'So it goes round and round the event horizon I suppose.'

'No, I am afraid not,' George said smiling and watching closely for my reaction. 'It is stuck at one point and stays put.'

'What, light gets stuck at one point?' I couldn't believe this. 'This is crazy, bizarre, unheard of…'

'Hold it, Alfie, before you exhaust your vocabulary,' George was highly amused. 'Yes, all phenomena associated with the black hole seem surreal. But all natural phenomena have natural explanations. You remember we talked about equivalence principle and about how gravity bends light?'

'I do.'

'We said that this meant that light slowed down as in a dense medium, like the way a mirage is created. However, for a freely falling observer, the light ray still travelled straight with constant velocity. Well, in this case too, for a freely falling observer light does not appear to be stuck at one place. It still travels with constant speed. Again, let me stress that it is a co-ordinate effect remedied by the Kruskal-Szekeres coordinates.'

'George, you told me that in the Kruskal-Szekeres co-ordinates, the apparent singular behaviour at the horizon is removed.' I said. 'From what you said just now, it seems like the behaviour of light also looks different in these co-ordinates. Am I right?'

'Yes, Alfie, you are absolutely right,' affirmed George. 'In fact the description of light propagation is a very important aspect of these co-ordinates. The co-ordinate speed of light is the usual universal constant everywhere just as in the flat spacetime. Again, the light cone structure too is exactly as in the flat spacetime. And this is a big help in understanding light propagation at the horizon.'

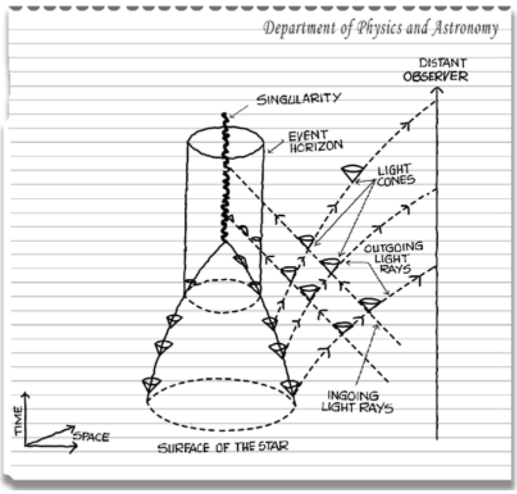
'All right, George, I'll buy your explanation. Still, I think the behaviour of light at the horizon is quite strange,' I shook my head. 'What happens if light is emitted inside the event horizon?'

'As you can see from the drawing, there is no such thing as an out-going wave at all now. The whole wave front is sucked into the singularity. No information can travel out.'

It was quite nice to understand the basics of the black hole with the aid of pictorial representation. But I had no doubt in my mind that it would be much more satisfying to grasp these simple but profound ideas by working out the mathematical framework. Well, there were more things to learn about at my own level.

'George, I have read that the appearance of a collapsing star as seen by a distant observer is radically different from the experience of one who may be riding on it. Can you show this on your diagram?'

'Why not? First let me draw the surface of the collapsing star creating the black hole. There, you have it. Now, mark equal intervals on the surface of the collapsing star. They represent equal divisions of the proper time measured by the hapless observer sitting on the surface of the star. Let him send a pulse of light at equal intervals to his cosy companion far away. In the beginning, the pulses arrive at the distant observer at the same equal intervals. As the star-stuck astronomer moves closer to the black hole the pulses arrive at intervals that are stretched out more and more. Furthermore, they appear redder and redder, and fainter and fainter. Finally it will take the infinitely red-shifted pulse infinite time to reach the far away observer. What is the end result of all this? What the distant observer sees is the surface of the star appearing progressively redder and fainter, inching towards the event horizon slower and slower, but never reaching it. Unfortunately, at the same time, you can see that the star



would have collapsed in finite proper time hitting the singularity, or rather creating the singularity, taking along with it its rider to his inevitable doom.'

'What a way to go!'

'Well, the end could come even earlier for the adventurous astronomer. As he falls, the gravitational force acting on his feet would be higher than his head, assuming that he is falling feet first, and not doing any gymnastics on the way.'

'The tidal force!'

'Ah, we discussed the tidal force at the horizon in detail just now, didn't we? Yes, as our astronomer nears the event horizon the tidal force may not be too high if the black hole is sufficiently massive. But sure enough somewhere along the line it would increase, stretching the man out of proportion. Those who have no appreciation for Italian food have the habit of saying he is turned into spaghetti and torn apart.'

'All this horror movie stuff apart, does this tidal force play any significant role at all?'

'You bet. It becomes quite important for astrophysics involving black holes, Alfie. For instance, if a star strays near, say a rotating black hole, tidal forces may shred it into bits that could become part of an accretion disk around the black hole. We shall talk about it later on, especially when we discuss the observational evidence for black holes.'

I thought we had covered the most essential part of the structure of black holes. But I was sure that the black hole manifested itself in many different ways. I was eager to learn as much as I could without taxing George too much. I let him rest for a while.

'George, I do hope you are not tired out,' I began. 'There must be plenty of physical phenomena going on around the black hole that differ from their Newtonian counterparts. Could you tell me a bit about them?'

'Sure, Alfie,' George was ready to tell me more, as I had expected. 'All physical phenomena get modified near the black hole. Take for instance the geodesics. We know that they are the paths of natural motion for both material particles and light rays. They also come in handy for analysing spacetime structure.'

'Sorry to interrupt you, George,' I said. 'I must tell you something interesting about geodesics in three-dimensional space. It seems that the hollow organs in our bodies like the stomach and the heart are made up of muscle fibres laid out along geodesics. Nature minimizes the material used.'

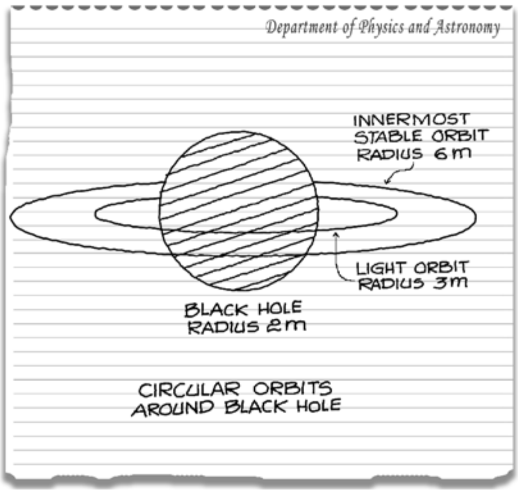
'Really! That is interesting,' remarked George. 'Of course, we cannot verify it in my office. Go on, you seem to have something more to tell me.'

'Well, the surrealist artist Salvador Dali says that the best way to draw the figure of a nude model is to draw the geodesics on her body. If you draw enough of them, then even if you remove her, the geodesics you have drawn should define her form for you. One of these days I shall show you the full details along with Dali's illustration accompanying his claim.'

'What do you know? It is just like geodesics defining the spacetime structure, Alfie,' exclaimed George. 'Don't tell it to my friends doing general relativity. They will rush to the nearest artist's studio and indulge in figure drawing. That too, on grant money.'

George shook his head and laughed, probably imagining his colleagues busy in their new occupation.

'All right, now. Let us get back to the geodesics in the Schwarzschild spacetime then,' resumed George. 'In Newtonian gravity, circular orbits of material bodies around a gravitating mass, like the Sun for example, can exist at all radii. But now this situation changes quite drastically. Before I go into details, let me tell you a convenient unit we use for the radial distances. This is denoted by *m* and is equal to the mass of the black hole multiplied by the Newtonian gravitational constant and divided by the square of the speed of light.'



'But that is nothing but half the radius of the event horizon, is it not?' I could figure that easily.

'You are right, Alfie. The radius of the black hole is 2*m*. Now beyond 6*m*, or beyond thrice the radius of the black hole measured from the centre, all circular orbits are quite stable. That is to say, the orbit at this radius of 6*m* is the innermost stable orbit as it is called. In the region beyond it, Newtonian gravity is quite a good approximation. Between the innermost stable orbit and 3*m*, that is one and a half times the black hole radius, there can only be unstable circular orbits.'

'What do you mean by unstable?'

'I mean that if you nudge a particle in such an orbit it will spiral down into the black hole. Below the orbit at 3*m* there are no circular orbits at all, stable or unstable. Particles in this region will have to fall towards the black hole. We have been talking about geodesic paths. But you do not have to move along only geodesic paths. As long as you stay outside the event horizon, you can follow any trajectory you like, for instance by riding on rockets.

'What happens at the radial distance of $3m$?' I asked. 'Is that some special kind of orbit?'

'Ah, your intuition at work, Alfie!' commented George. 'Yes, it is a very special orbit. Light can go round and round in circles there. It is a geodesic for light not for material particles.'

'That is very strange I must say, George. Light that normally travels in straight lines now moves in a circle!'

'Didn't you remark that in a crooked world the straight path is crooked too?' George reminded me of what I had said. 'That is what is happening here. Light travels in a circle at this radius. You can move along this orbit too, but your path won't be a geodesic. Suppose someone has built a circular tunnel at this radius and you are following another car in this tunnel. You will always see the taillight of the car in front of you because light travels along this circle. You will feel that you are moving in a straight line in a straight tunnel. Even your centrifugal acceleration would be zero.'

'That is weird,' I said. 'But of course one should expect the unexpected when dealing with black holes, I suppose. Tell me, do these geodesics have any practical value, I mean, astrophysically speaking?'

'Of course, Alfie. For instance, if you know the speed of a star orbiting the black hole and the radius of its orbit, you can calculate the mass of the black hole. You will see how this works when we discuss the detection of black holes. Then again, if you want to study the gravitational radiation emitted by sources moving around the black hole, you have to know their paths. I must add that these trajectories need not be just circular. One could be considering a radially in-falling source or the one that may be spiralling down into the black hole.'

'Aha, you inadvertently opened up a new topic, George,' I pointed out.

'What is that?' asked George a little surprised.

'Gravitational radiation.' I answered.

'Nothing inadvertent about it, Alfie,' responded George. 'I was going to tell you about it anyway, a very important aspect of general relativity.'

'The ripples set up in the acrobat's net when the fallen acrobat jumps up and down in helpless fury,' I said, referring to the cartoon George had shown me.

'A picture says more than thousand words, right, Alfie?' smiled George. 'You know this incredible man Albert Einstein predicted the existence of gravitational waves too. Not only that, but he derived the energy that is carried away by these waves. Einstein did his calculation assuming that the motion of the sources, such as two bodies going round each other, and the propagation of the waves emitted by them, all occurred in a flat spacetime. This is a very important calculation no doubt. But we would like to know what happens if the phenomenon takes place in the gravitational field of a black hole. This is essential for astrophysical applications.'

'You said the source of gravitational radiation could be some object, say a star, moving along some geodesic in the Schwarzschild spacetime.' I recounted. 'But how do you handle the gravitational radiation part of the problem?'

George paused. This meant he was opening up a new topic altogether.

'This has to do with the perturbations of a black hole, Alfie. It is an important field in its own right,' began George. 'Let us start with the Schwarzschild spacetime. Now this spacetime can be changed ever so slightly by external influences such as a particle falling into the black hole or orbiting it.'

'A small clarification, George,' I interrupted. 'What do you mean by a particle in this context, some regular object like a star or what?'

'It could be any kind of object including a star. The criterion is that this object should not change the geometry of the spacetime appreciably. That is why we consider it to be a particle or a test particle as it is called.'

'All right, go on then.'

'In the examples I gave, the slight change in the background Schwarzschild spacetime would be in the form of gravitational waves. Even without invoking the source of the gravitational waves like the test particles one can think of just gravitational waves propagating in the Schwarzschild spacetime. Do you follow?'

'Yes, but how do you express this in mathematical terms?' I asked.

'Simple, Alfie. Take the Schwarzschild spacetime metric and add to it terms, which are very, very small compared to the original metric components. These new terms are known as the perturbations of the black hole. Feed them into the Einstein field equations and you can get equations that govern the behaviour of these perturbations. You can study them and get plenty of information on phenomena occurring in the gravitational field of the black hole.'

'Such as, for instance?'

'One important problem that was handled by the perturbation theory, as it is called, was the stability of the black hole. The stability of a system is a very general problem you know. To begin with you can think of any system in a state of equilibrium. But one would like to find out whether it could continue merrily in that state. For this, it has to be not only in equilibrium but stable too. We already saw how the circular orbits can be stable only down to the innermost stable orbit. Only those can exist in nature. The ones between this orbit and the circular photon trajectory are in a state of equilibrium, but are not stable. Therefore, they cannot have continued existence in nature.'

'Seems interesting,' I remarked. 'But is this important?'

'Oh, yes, Alfie. It is very important in building and studying accretion disks around black holes. We shall talk about this aspect when we consider the rotating Kerr black hole. These orbits play a major role in detecting black holes too.'

'All right, what about the black holes themselves?'

'I was coming to that. In this case, the system we want to examine is the black hole, which corresponds to an equilibrium state. To find out whether it is stable or not, you perturb it. If the perturbation dies down, or oscillates, then the black hole is stable. If the perturbations grow with time and blow up, then of course the black hole is unstable.'

'Well, as I have told you time and again, George, there is always a human analogy hidden in these things,' I said. 'The true nature of human beings is also revealed only when they are perturbed. When perturbed, humans too can either stay cool and be stable or blow up. In any event, what was the outcome of the perturbation studies on the black hole?'

'Well, the Schwarzschild black hole was proved to be stable,' answered George.

'I suppose this was as important as the stability of the orbits.'

'More so, Alfie. This meant that a black hole could exist as a stable entity. So relativists could continue their exploration of this strange object. Astrophysicists could think of how it enters into their observations and models to explain them.' George added in a mock whisper, 'And make a living out of all this.'

'Ah, that way the black hole could move from abstract theory to pragmatic reality.'

'You are right, Alfie,' said George. 'We started on this topic to get a hold on gravitational radiation, didn't we? Well, one can use perturbation techniques to compute gravitational radiation emitted by particles falling into the black hole or orbiting it, and so on. But more important, the perturbation formalism also revealed the existence of what is known as the *quasi-normal modes* of the black hole vibrations, which carry the imprint of the black hole.'

'Ah, the mark of the black hole! Like the Mark of Zorro,' I exclaimed.

'Exactly! These quasi-normal modes showed up in the process of gravitational-wave scattering. Let me explain. How do we see an object or detect one directly? It is through the process of scattering. A macroscopic body becomes visible because it scatters light. An atomic nucleus reveals itself by scattering elementary particles. In fact, that is how Rutherford discovered the atomic nucleus in the first place. After the Schwarzschild black hole was shown to be stable, the natural question to ask was how to detect it. The answer was obvious. Why not detect the black hole the same way as all other objects are observed in nature, namely though the scattering phenomenon? Why not pelt the black hole, disturb it, and make it show itself up?'

'Pelt the black hole? With what? Anything you hit the black hole with would be swallowed up by it, wouldn't it?' This was becoming curiouser and curiouser as Alice would have put it. Come to think of it, the entire black hole story had the whimsical character of Lewis Carroll's *Alice in Wonderland*.

'Alfie, a material particle hitting the black hole would be gobbled up, yes,' answered George. 'But a wave would be scattered by the gravitational field of the black hole. Part of it is swallowed up by the black hole no doubt, but the rest travels out to a distant observer. So the study of this scattering was taken up. All this was theoretical calculation, mind you. Probably the first time computers were used in general relativity to give some tangible results. Nowadays, computers are extensively used for numerical work and also for algebraic calculations in general relativity. Well, coming back to our problem, you send in a wave pulse, or a wave packet as it is called. This is what I meant by pelting the black hole.'

'What happens then?'

'Then the wave packet is scattered off the black hole and you can observe the out-coming waveform. If the in-going pulse is large in extent, nothing unusual happens. It is just like a big wave washing over a small pebble. But if you make the pulse sharp enough something remarkable happens.'

'What is that?' I asked with interest.

'A waveform of a fixed frequency but diminishing in amplitude emerges. Let me give you an analogy. Tell me what happens if you hit a bell?'

'You hear the sound of the ringing bell that has a characteristic pitch,' I answered.

'What about the loudness of the sound?'

'It progressively decreases.'

'That is exactly what happens here. The out-coming gravitational-wave pattern is like the pure dying note of a ringing bell. The interpretation is that you excited the black hole by sending in a disturbance, in the present case a gravitational wave pulse. And the black hole vibrates, generating a decaying wave at a characteristic frequency. As I said, it has come to be known as the quasi-normal mode of the black hole.'

'This is quite interesting, George,' I said. 'But, where is the mark of the black hole?'

'The answer, my dear Alfie, is obvious. It is the characteristic frequency that carries the signature of the black hole. First, the quasi-normal mode by itself reveals to you the existence of a black hole. Further, the frequency gives you the information on the black hole parameter, namely the mass.'

'Tell me, do these modes figure anywhere else or only in the scattering of gravitational waves?'

'Excellent question, Alfie,' George nodded approvingly. 'It so happens that these modes invariably appear in almost all processes involving black holes. For instance during the formation of a black hole by gravitational collapse gravitational waves are emitted, if asymmetries exist in the collapsing mass distribution. We shall talk about gravitational waves again, when we discuss the detection of black holes in greater detail. But let me just mention that gravitational radiation is also generated when two black holes coalesce. In both cases, during the last stages, quasi-normal modes appear. So you see, these modes do tell you about the black holes in a direct way.'

George fell silent. I felt I had taken enough of George's time.

'We must have covered most of the stuff related to the Schwarzschild black hole then,' I said.

'Oh, no, Alfie. Let us say we have just scratched the surface of the black hole, the most basic aspects of its properties,' replied George. 'There are more fundamental issues and quite a bit of physics that takes place in the gravitational field of a black hole. We shall touch upon some of them one of these days,' said George. After consulting his black board on which he had written down his appointments with a box around each of them, he told me, 'Drop in tomorrow same time and we shall discuss the basics of the rotating Kerr black hole.'

'All right, George. How about a short stroll and a bite now?' I invited George.

'Get thee behind me, Alfie,' George shook his head. 'Don't tempt me. How I wish I could join you. But soon my three graduate students will be here bringing along some sandwiches. I have to spend an hour or so discussing their research problems with them. After that I have to give the finishing touches to a grant proposal I have to submit by tomorrow. My bread and butter you know. After that… Oh, forget it. I don't want to think about all this right now after the pleasure of talking to you.'

‘I don’t envy you, George, at least not the chores you have to perform. Good night and take care.’

‘You too, Alfie. Till tomorrow then.’

I looked back before leaving the room. George was already standing in front of the blackboard, stroking his chin, deeply engrossed in the equations he had written earlier. I quietly stepped out into the dimly lit corridor closing the door gently after me.

Chapter 13

THE VORACIOUS WHIRLPOOL

'B*uenos tardes*, *Señor* Alfie. How you doing?' called out Fernando as I passed by his little store. I was on my way to the university for my meeting with George. Fernando was dressed formally in somewhat outlandish attire, which was quite unusual for him. He was sporting a jacket and a bow tie with polka dots, and was wearing a large hat, which must have been quite new, since he had forgotten to remove the price tag. Incidentally, Fernando is a collector of hats, and owns an assortment of them. The one he was wearing must have been the most recent acquisition. Maria wore a deep red dress and a matching hat. Falicia, dressed in a white frock, had brought out her whole menagerie of animals. Her rabbit, Blanco, was darting nervous looks everywhere; a small furry-tailed animal that looked like a cross between a mouse and a squirrel nested drowsily in her lap; the sad turtle, Macho, was stationed beneath her chair, while a cat lazed nearby. The family was seated at a table covered with tablecloth, on which were laid out a teapot and teacups accompanied by a basket filled with rolls and slices of bread. There seemed to be a party going on.

'*Señor* Alfie, meet our guest *Señor* Marchado Harera,' said Fernando.

Like Fernando, *Señor* Harera was also formally dressed in striped trousers, jacket, a garish vest adorned with flower patterns, and a bow tie. He waved at me with his large paw-like hand and flashed a wide grin displaying his two prominent front teeth.

'Have some tea, *Señor* Alfie,' invited Maria and added, 'sorry, we don't have any wine. Too early for that, you know.'

It was already getting late for my appointment with George, so I made my excuses wishing them all a happy party, and went on my way to the university.

'Come on in, Alfie,' George greeted me effusively in his usual manner as I knocked and entered his office. 'Look at these beauties,' he added pointing to a tray on his desk.

The tray held an assortment of science toys meant for classroom demonstration. George picked up a beautifully crafted, old-fashioned gyroscope, wound up the string provided at its base, and pulled it out in one quick movement. The gyroscope spun quietly, pointing steadily in a fixed direction.

'I show these toys in my class, Alfie. Students just love them. Much more interesting than working out equations without knowing what they mean in the real world,' said George.

'Maybe one of them could be inspired like Einstein was at the sight of the magnetic compass,' I commented.

'Maybe, who knows, although I wouldn't bet on it,' said George. 'Look at that gyro, isn't that terrific?' He watched the gyroscope with fascination as if he were seeing it for the first time. 'Do you know what I think of whenever I look at the gyroscope, Alfie? The whole Earth! Can you imagine our enormous Earth spinning like that? Not only that. Can you visualize this gigantic top, our Earth, wobbling as well? As the Earth goes round the Sun, its axis precesses because of its non-spherical shape. I am sure you know all this.'

'I know, George,' I said. 'I also happen to know that you can't find the verb *precess* in most dictionaries, with some exceptions; you can find only the noun *precession*s.'

'Well, if the verb *precess* didn't exist, it ought to be invented,' George was unruffled. 'It is so convenient, don't you think? What was I saying? Yes, the Earth precesses as it revolves round the Sun.' He emphasized the word *precesses* deliberately.

'What was I going to say?' I echoed George. 'Yes, the Earth precesses with a period of 26,000 years. So what we call the Pole Star, the star in the direction of the spin axis, changes too over that period. Even the ancient Greeks knew that. Throws astrology out of gear, doesn't it? Mixing up the constellations. Not that one should believe in astrology in the first place.'

'You are perfectly right for once, Alfie.' It was a comment George liked to make from time to time. 'Again, it was our friend Isaac Newton who explained it. You find rotation everywhere in nature, Alfie. All stars rotate, as a matter of fact. When they collapse and die, the end products rotate too, the white dwarfs, the neutron stars, and the black holes. In fact, rotating black holes are extremely important objects, both from conceptual point of view and for astrophysics.'

'Well, that is what we are going to talk about, aren't we?' I prompted.

'That is why you are here, aren't you?' replied George. 'Let us go and sit down comfortably in our cosy corner.'

George led me to the low table with comfortable chairs near the blackboard. As before, on the table lay George's writing pad, pens and a few sheets of photocopied material. I noticed that new equations had appeared on the blackboard.

'George, before you start on rotating black holes I have a couple of questions on Newtonian gravity,' I said.

'Fire away, Alfie,' responded George.

'Well, Newton himself showed that the Earth is not a sphere but has an oblate shape due to its rotation. I know that this is a small effect. Still, it should show up in the gravitational field of the Earth.'

'Sure. The gravitational field no longer possesses spherical symmetry. On the other hand, Earth's shape and consequently the gravitational field exhibit almost perfect symmetry about the axis of rotation barring some minor deviations. Draw a circle about the axis and the field would be the same at all points on it. But the field varies from circle to circle depending on their radii. This is known as axial symmetry or rotational symmetry.'

'All right then. Now suppose you construct an object which has exactly the same shape as the Earth but does *not* rotate. Then is there any difference in its gravitational field as compared to the rotating Earth?'

George inclined his head in his characteristic manner and looked at me for a moment before saying approvingly, 'Very nice question, Alfie. The answer is 'No', as far as Newtonian gravity is concerned. On the other hand, within the framework of general relativity, rotational effects do show up quite distinctly in the spacetime structure or equivalently in the gravitational field. Would you be surprised if I told you that these effects have invaded our own lives?'

'How is that, George? I thought that general relativistic effects are so minute that they become significant only on astronomical and cosmological scales,' I was truly surprised by George's remark.

'So did everyone till the invention of the Global Positioning System. Remember I told you that Newtonian gravity was adequate for all practical purposes with one exception? This is it. I am sure you know all about the present rage called GPS.'

'In principle, yes,' I answered. 'There are these satellites up in the sky that keep transmitting signals that tell you their own positions and the time at which the signals were emitted. From this information the little computer in your GPS deduces accurately where you happen to be.'

'That is correct. But don't forget you are in a rotating frame as the Earth spins. Exactly like Einstein's rigidly rotating disk. To make your calculations, you forget the gravitational field of the Earth in the first instance, and switch over to the rotating frame by a simple coordinate transformation. Rotational terms appear in the otherwise flat spacetime.'

'So?'

'So these rotational terms affect important operations like the synchronization of clocks and time measurement. Also these terms produce additional effects like redshift and so on. Unless these relativistic corrections are taken into account, your GPS won't be accurate at all. And this accuracy is crucial to all sorts of things, let alone in locating the nearest pub. For instance, communication, surveying and mapping, guiding commercial aircraft, navigation in deep space, measurements on pulsars and what not.'

'And warfare is an integral part of the what not, I suppose,' I added.

'Unfortunately, that too, Alfie.'

'Once again, as with his mass-energy equivalence, what would Einstein have thought about his rigidly rotating disk had he know about this last item? God or someone else leading him by the nose and having a good laugh?'

'Can't help it, Alfie, we can only discover the genii in the bottle, but cannot control it once it is let out,' George said. After a pause, he continued. 'You know, the rotational effects that arise here are merely due to the passage from a static frame in the flat spacetime to a rotating one. Just like inertial forces appearing in Newtonian physics. In both cases these effects disappear if you go back to the non-rotating frame. But, you can have real spacetime effects due to a rotating source that just cannot be removed. They show up if you have an exact solution to Einstein's field equations corresponding to a rotating source.'

'Weren't such solutions for the gravitational fields of rotating stars discovered after Schwarzschild gave his spacetime of a non-rotating sphere?'

'No, not for nearly four decades you know,' George shook his head. 'Not until the exact solution for the rotating black hole was found. Roy Kerr, a relativist from New Zealand made this important discovery in 1963.'

'I suppose he was trying to modify or extend Schwarzschild's spacetime to include rotation so that the black hole would be rotating too,' I guessed.

'Not at all,' said George. 'Let me explain. First of all, nobody really bothered about black holes till the sixties. Moreover, after its initial spectacular success, general relativity sort of went into hibernation. Some relativists were busy analysing the structure of Einstein's field equations. Some were generating and classifying exact solution to those equations. And others were working out highly mathematical formalisms. Take a look at Kerr's original paper. It will give you a feeling for what was going on.'

George fished out Kerr's paper from the bunch of photocopied material lying on the table. It bore the rather technical-sounding title, *Gravitational Field of a Spinning Mass as an Example of Algebraically Special Metrics*. The short paper, which ran to a mere page and a half, was quite mathematical.

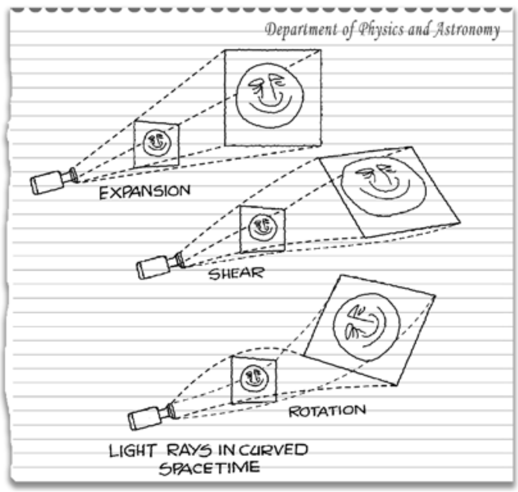
'You see, Alfie, all possible spacetimes have been classified into a handful of species based on the nature of the spacetime curvature,' George explained. 'Relativists have been trying to find exact solutions, or metrics, which are the same thing as we saw, corresponding to these different species. In doing that, sometimes they also stipulate the properties of light rays that are fundamental to the spacetime.'

'Sorry George, I don't understand your last statement,' I declared.

'I know. It is a somewhat technical detail but not incomprehensible. It has to do with the bending of light rays in a gravitational field.'

'Which Einstein himself demonstrated,' I added.

'Right, but let us add some more details to what Einstein did,' George went on. 'Think of the rectangular image a movie projector throws on the screen. If the cinema hall happens to be situated in a sufficiently complex gravitational field, then the light rays starting from the picture frame can undergo all sorts of changes affecting the projected image. Normally they just diverge and enlarge the picture. But they can be deformed, or sheared as the technical term goes, so that the rectangle is squashed into a parallelogram. The light rays can also twist and turn, rotating the picture.'



'If all these things happen to the light rays from the projector, then Marilyn Monroe might look like Bela Lugosi hanging upside down like a vampire bat! No one will ever go to a movie then,' I laughed.

'Alfie, I know you are a movie buff. Luckily for you, these distortions do not occur in the Earth's weak gravitational field,' said George. 'But it can happen in principle given the appropriate spacetime. And Kerr was looking for a particular species of spacetime – algebraically special as it is called – that admits fundamental light rays that twist as well as diverge. And he found it. In the paper he points out that the Schwarzschild spacetime is a special case of his solution. He also identifies two parameters as mass and angular momentum. Beyond this the exact nature of the spacetime was not at all clear. See what he says at the end of the paper.'

I read the last sentence: *It would be desirable to calculate an interior solution to get more insight into this*.

'Did Kerr find an interior solution just as Schwarzschild did?' I asked.

'No, Alfie. And no one has found one ever since,' George shook his head. 'As a matter of fact, there are indications that such a material source may not even exist. In all probability, the Kerr solution describes the spacetime of a rotating black hole exclusively. After it was discovered, it took several years of exploration to understand the properties of this spacetime. And that is what we are going to do now. But first, we need some fuel to keep us going, don't we?'

George went over to his second desk piled up with papers, and brought back his thermos flask of home-brewed coffee and paper cups together with a paper plate full of little pastries.

'You know, once a week we have this tea when the entire department shows up,' explained George. 'Really nice with snacks and all. It is where the students can catch hold of their elusive thesis advisors. Members of the faculty discuss their problems informally with the Chairman. And of course we are not above doing a bit of gossiping to follow the academic grapevine. Today was the tea day and I pinched some stuff for us to eat.'

George poured coffee into two paper cups. I tried a thick biscuit with chocolate chips and blueberries on it as I sipped the hot brew. It was delightfully satisfying.

'Alfie, yesterday we went over the Schwarzschild black hole in great detail,' began George. 'This was essential in order to understand the basic concepts of black hole geometry and physics. Today we shall make the Schwarzschild spacetime our point of reference so we can compare and contrast it with the rotating Kerr black hole and its spacetime. I don't have to keep asking you whether you remember our earlier discussions, do I?

'No need at all, George. At home, I go over the notes and diagrams to recapitulate whatever we have discussed,' I assured him.

'Good. First metric functions or just metrics as we call them then. Schwarzschild was time independent and was spherically symmetric. The source had no motion at all. Now we have a uniformly rotating source for Kerr.'

'Going by the Newtonian analogy you described, the spacetime must have axial or rotational symmetry too. Which means, on any circle drawn around the rotational axis, the spacetime structure must be the same, but varies with the radius of the circle.'

'Perfectly right. How about time symmetry?' George led me on.

'Let me see. I suppose the rotation of the source is uniform, unchanging with time. Then again, its shape also remains fixed. So, everything remains the same when viewed from outside. Therefore the spacetime must be independent of time or time symmetric as before.'

'Right again. So the Kerr spacetime has just two symmetries, one with respect to time and the other with respect to the rotation axis. There is no spherical symmetry unlike as in the case of Schwarzschild.'

'I guess those symmetries are reflected in the form of the metric functions, since they decide the spacetime structure.'

'Yes, indeed. The metric functions are independent of time and independent of the angle of rotation about the vertical axis, which is taken to be the spin direction of the black hole.'

'Fine, but how does the rotation built into the spacetime figure in this?'

'Well, Alfie, the Kerr spacetime is characterized by two, not one, parameters. There is the mass M, obviously. As we did in the case of Schwarzschild, it is convenient to define a quantity *m*, which is the product of the mass and the Newtonian gravitational constant divided by the square of the speed of light. In addition, there is the angular momentum of the black hole, call it J, as well since it is rotating. In most calculations, the angular momentum J divided by the mass M, denoted by *a*, makes its appearance. As for the metric functions, there is one additional term, which is a product of time and the rotational angle. It is proportional to *a*.'

'Such a term didn't exist in the Schwarzschild spacetime, did it?' I recalled.

'No, Alfie. And this term crucially represents the rotation inherent to the Kerr spacetime.'

'The metric functions in the Schwarzschild spacetime were absurdly simple. How about now, George?' I enquired.

'I am afraid they are quite complicated, Alfie,' George told me. 'Let me confess. Even after all these years of working on black holes, I cannot remember these functions properly.'

'That is comforting, George. Then I don't have to memorize them either.'

'One nice thing though. If you set the angular momentum, or *a*, to zero, you recover the Schwarzschild spacetime and correspondingly the non-rotating black hole.'

'Kerr himself points this out in his original paper, doesn't he? Obviously, he doesn't talk about black holes,' I said. 'Now, since the Kerr black hole is an isolated source of gravity, as was the Schwarzschild black hole, I suppose the gravitational field falls off at large distances.'

'Quite right,' George concurred. 'Far away from the rotating black hole the spacetime can be taken to be flat for all practical purposes.'

'As before, we can think of static observers in the flat regions of spacetime then, floating at fixed positions, with no gravity acting on them, can't we?' I enjoyed leading the discussion.

'You are on the right track, Alfie. Yes, we can have such static observers. They are special observers, because their spatial positions are fixed and they just follow the flow of time. All right, as we did in the Schwarzschild case, let us move on towards the black hole.'

'Ah, now the long fingers of gravity gently pull the observers inwards. And in order to remain static, fixed at the same place, the observer has to ride a rocket whose thrust counters the inward tug of gravity.'

'Alfie, let me make a couple of things clear before we go on,' George held up his hand. 'First, a slight change in terminology, just a technicality, you know. Whenever there is rotation, the word *static* is replaced by the word *stationary*. So instead of the Schwarzschild static black hole, we now have the Kerr stationary black hole. In place of static observers, we have stationary observers. As I said, just a matter of labelling. But we can use the two terms interchangeably for convenience. Next, the inward pull of gravity is not purely radial as was in the Schwarzschild case. The rotational effect of the spacetime is to make the observer tend to have a rotational motion as well. Therefore your rocket's thrust will have to counter the resultant force.'

'So suppose I just place a few free particles in space. What happens to them?'

'They fall towards the black hole spiralling their way down. This is quite important from the astrophysical point of view too. Suppose your black hole is accompanied by another star: the two going around each other as a binary system. Matter from the second star, perhaps a bloated red giant, could stream towards the black hole. This matter, spiralling inwards, forms a disk around the black hole. This is known as an accretion disk.'

'Why a disk?'

'Let me do a little bit of explaining,' said George. 'Matter from one of the stars can accrete on to the other in radial directions also without forming a disk. But, when the two stars are going around each other, and the matter streams out rotating, an accretion disk is formed. If one of the stars happens to be a rotating black hole, the effect can be even more accentuated. The rotation built into the black hole spacetime tends to confine the matter to the equatorial plane Now you know why...'

'George, I noticed something,' I wanted to get some clarification on a peculiar characteristic of the manner in which George was explaining the Kerr spacetime to me. 'You keep referring to *rotation inherent to* or *built into the spacetime*. But I have come across descriptions of the spacetime itself as a seething, swirling entity, a voracious whirlpool with the black hole at the centre. But let me confess. I can't imagine empty spacetime whirling away by itself.'

'Don't even try, Alfie,' cautioned George. 'The black hole is a voracious beast all right, swallowing up everything that enters it. And the matter spiralling into the black hole can form a maelstrom. But the space itself does *not* rotate, contrary to the popular folklore. It makes matter rotate, that is all. Tell me, what happens to matter in the Schwarzschild spacetime?'

'It tends to fall radially into the black hole. We know that,' I answered.

'Does that mean that the space itself is collapsing into the black hole? Certainly not! It is the same here.'

'But you do have spacetimes that sort of have motion of their own, don't you? Like the expanding universe.'

'Sure thing, Alfie, those spacetimes are time-dependent unlike the black-hole spacetimes. In other words, their metric functions depend upon time,' elucidated George. 'You know the popular two-dimensional analogue of the expanding universe. It is the surface of a balloon that is being blown up. I am sure you have come across it. Place dots over the surface with fixed spatial locations to mark the galaxies. As the balloon expands, the distances among the dots increase. Light gets stretched too, leading to the cosmological redshift of the galaxies, which itself varies with time. This kind of thing does not happen in the case of black-hole spacetimes. Points with fixed spatial coordinates, like the locations of the static observers, do not move around the black hole. As a matter of fact, a literal interpretation of the Kerr spacetime as a rotating entity can lead to wrong results sometimes.'

'Do I take it then that to think of the spacetime itself as rotating is at best a metaphor and at worst a mistake?'

'Very well put, Alfie,' George nodded his approval. 'Let me give you an electromagnetic parallel to illustrate the difference between the Schwarzschild and the Kerr black holes. Take a sphere carrying say, positive charge. It produces a purely radial electric field. Negative charges are attracted towards it. Of course positive charges are repelled. In the case of gravitation it is only attraction. Gravity acts like an attractive electric field. Now rotate the charged sphere. In addition to the electric field, a magnetic field is now generated as well. And charges tend to rotate in the magnetic field. This is a characteristic property of magnetic fields in fact.'

'I know. That is how charged particles go round and round in the magnetic field of an atom-smasher like a cyclotron.'

'Exactly. Now let us talk a bit more about the rotation of the Kerr spacetime and magnetic fields. Incidentally, did you notice, Alfie, that I have dropped phrases like "inherent to" or "built into", now that we understand that the spacetime does not actually rotate? That is what most relativists do for convenience, knowing fully well that the space itself does not rotate. But you must watch out for any literal interpretation of spacetime-rotation. To continue: The rotation of the spacetime acts very much like a magnetic field. As a matter of fact, the rotational effects of spacetime go under the name of *gravitomagnetism* and produce effects similar to a magnetic field. For instance, the spin of an electron placed in a magnetic field undergoes precession. Likewise, a gyroscope situated in the gravitational field of the Kerr black hole precesses too.'

'You mean this does not happen in the Schwarzschild spacetime?'

'Let me make myself quite clear,' stressed George. 'If you carry a gyroscope in an orbit around the black hole, either Schwarzschild or Kerr, the gyroscope undergoes precession. But a static gyroscope held at the same place precesses only in the Kerr spacetime, but not in the Schwarzschild. This is entirely a spacetime rotational effect. Some more coffee, Alfie?'

George replenished our empty cups and nibbled a biscuit. He smiled to himself at some amusing recollection. I waited for him to speak up.

'You remember our young astronomer friend Mike Brown, Alfie?' asked George.

'Oh, yes, George. I met him the other day when we were discussing Newtonian physics over lunch, didn't I? Quite a nice chap he was,' I recalled.

'Right. He jogged in circles around us. When I complained that he was making me dizzy, he said it was a Machian effect.'

'Oh, yes, I remember that. But tell me, who is this Mach? Is he the same one after whom the unit for the speed of sound is named? One indicates supersonic speeds like those of aircraft in so many Machs.'

'The same one, Ernst Mach, the distinguished Austrian physicist,' confirmed George. 'His ideas had a profound influence on Einstein, you know.'

'But how does he figure here?'

'Well, there is something called Mach's Principle,' explained George. 'There are several formulations of Mach's Principle. Mach speculated that all bodies had some kind of influence on one another. In fact, according to his Principle, the inertia of a body is determined by the entire mass distribution in the universe. Let us not get into this complicated affair, which is a big topic in itself. For our purpose, it is sufficient to say that a manifestation of this Principle is that if you have a rotating object, it induces rotation in another object too. That is the Machian effect.'

'Ah, now I understand what Mike meant,' I said. 'He was the rotating source and your dizziness was the Machian effect! All right, let us get back to the Machian effects in the context of a rotating black hole.'

'Well, the gyroscopic precession is considered to be a Machian effect. The Kerr black hole rotates. Its rotation is imparted to the spacetime, which, in turn, shows up in the gyroscopic precession. By the way, this is where a literal interpretation of spacetime as swirling like a whirlpool, thereby causing the gyroscope to precess, can go wrong. It so happens that the gyroscope reverses its direction of precession near the black hole. But the direction of the rotation of the spacetime does not. So you cannot directly correlate the sense of gyroscope precession with the so-called whirlpool effect of the Kerr spacetime. Some people call this reversal of the direction of precession an anti-Machian effect. Let us leave these subtleties alone and get on with the basics of the black hole.'

'Which means we go back to our stationary observers then?'

'Precisely. Isn't it amazing, Alfie, that the mere state of rest can reveal so much about the spacetime structure?'

'Yes, I can see that. I suppose things happen similar to what we saw in the Schwarzschild case. As we move towards the black hole, the rocket thrust needed to keep the observer stationary must steadily increase.'

'Right.'

'Then again, there is the redshift,' I continued my recapitulation. 'Suppose light is emitted by a stationary source placed in the strong gravitational field nearer to the black hole. It must get redshifted as it reaches a distant stationary observer situated in a weaker gravitational field. Which also means that the clock attached to the source runs slower when compared to the one belonging to the distant observer.'

'Yes, just as it happens in the Schwarzschild spacetime.'

'Does rotation have any influence at all on the redshift, as it has on the force acting on the stationary observer?'

'To some extent, yes. Light rays travelling from the source to the observer curve around due to rotation. Also, the redshift itself would involve the angular momentum of the black hole.'

'All right. As we move towards the black hole, both the rocket thrust and the redshift keep increasing. Finally we reach a point, or a surface, on which both of them become infinite.'

'Exactly. You are doing great, Alfie. Go on with your journey towards the black hole,' urged George.

'On this surface and beyond, an observer cannot stay put at one fixed place. This is the stationary limit. Also, redshift tends to infinity as we approach this surface. Therefore the stationary limit acts also as an infinite redshift surface. This happened in the case of the Schwarzschild black hole also.'

'You are absolutely right. The stationary limit and the redshift surface are identical both in the Schwarzschild and the Kerr.' George confirmed with a mysterious smile.

'Aha, so we have hit the black hole then,' I said triumphantly.

'You would be absolutely right in the Schwarzschild case, but you are absolutely wrong in the Kerr spacetime,' chuckled George.

I was puzzled. I was sure that George's mysterious smile meant that he had anticipated this all along.

'Where did I go wrong?' I asked.

'You didn't go wrong at all, Alfie,' answered George. 'You just hit the stationary limit, which is also the infinite redshift surface for stationary sources and observers. But, that is *not* the black hole in the Kerr spacetime.'

'All right, I have hit the stationary limit then. You cannot stay at rest on this surface and beyond. Then once you enter this surface, you have to fall into the black hole or the event horizon wherever that might be. Isn't that so?'

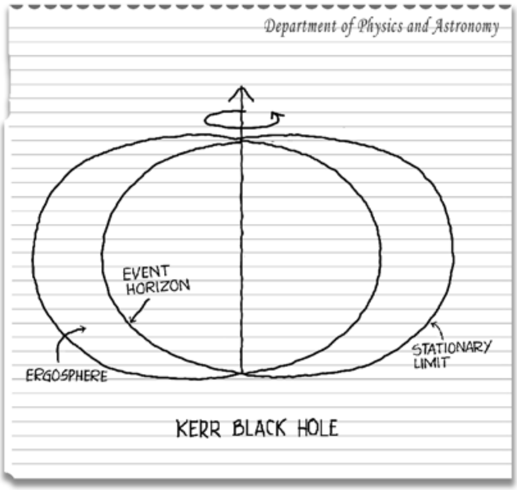
'Not necessarily. An observer who enters the stationary limit can still fly around in a curve and come out. You see, it so happens that the stationary limit is not a one-way membrane at all. You remember this was the crucial property of the black hole? The Schwarzschild black hole happened to possess all three characteristics, namely those of the static limit, the infinite red shift surface, and the one-way membrane.'

'Oh, yes, I remember the one-way membrane quite well,' I recalled. 'It is like a wave front frozen in space and time, isn't it? You can enter it but cannot come out unless you can travel faster than light, which is impossible.'

'That is right. Last time we discussed the light-cone structure in the Schwarzschild spacetime, didn't we? In the Kerr spacetime, it is more complicated since the light rays are also twisted in the same way as the particle trajectories. Anyway, the light cones are not tangential to the stationary limit, but they *are* tangential to the event horizon. That is why you can come out from the stationary limit, but not from within the event horizon.'

'Where is this event horizon in the Kerr spacetime then?'

'Nestling within the stationary limit. The two surfaces are split up by rotation. They touch each other on the axis of rotation at the poles.'

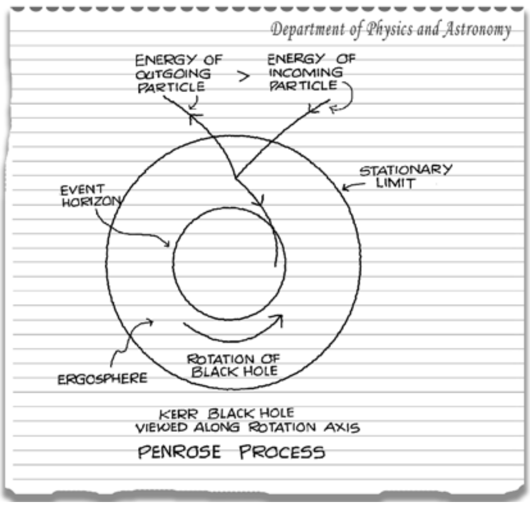


'Ah, I remember the pictures in popular books on black holes, George.' I had seen such pictures in many places. 'A spherical event horizon within an oblate stationary limit.'

'Well, the event horizon is not spherical, Alfie,' said George. 'It is represented like that, that is all. You could determine the polar and equatorial circumferences and find them unequal which means that the horizon is not a sphere. Or if you compute the surface curvature, it varies over the surface. But there is axial symmetry though. On a circle described around the axis of rotation, the curvature remains constant. And, of course, the stationary limit is an oblate surface. And the region between the two surfaces is known as the *ergosphere*.'

'Two questions, George,' I needed a little bit of information. 'Obviously, the structure of the Kerr black hole is more complex than its Schwarzschild counterpart. It must have taken quite a bit of complicated work to determine this.'

'Not really, Alfie,' clarified George. 'The nice thing is, all this structure drops out from the two symmetries of the Kerr spacetime and its rotation. The calculation is quite elegant you know. What next?'



'Why the name *ergosphere*?' Strange name I thought.

'Well, it is derived from the Greek word for energy,' answered George. 'Energy can be extracted from the rotating black hole. It is rather an unusual process. And it can occur only in this region.'

'That is interesting. I always thought that the black hole just went on capturing and swallowing up whatever came its way. I didn't expect that the black hole could yield anything at all. Tell me about this energy extraction of yours.'

'Not mine, Alfie, but Penrose's. It is called the Penrose process, named after the celebrated relativist, Roger Penrose. He pointed out the theoretical possibility of energy extraction from a rotating black hole. Here is how it works. You shoot an object, say a projectile, into the ergosphere. Let it split into two fragments. Now arrange cleverly for one of the pieces to fall into the event horizon in a direction opposite to that of the rotation. The other fragment now flies out with an amount of energy that is larger than that of the original projectile. So you have extracted energy from the black hole.'

'Where did this extra energy come from?'

'You see, in this process the rotation of the event horizon is slowed down by the in-falling particle. It is this decrease in the energy of the black hole that is imparted to the fragment that flies out.'

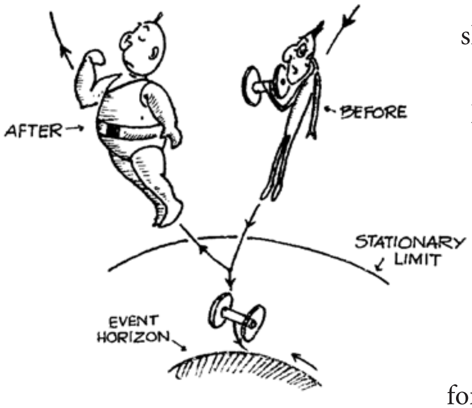
'How long can this process go on? Not indefinitely I suppose, since then we would be squeezing out infinite amount of energy from the poor black hole.'

'Of course not. You can go on pumping out energy from the black hole until its rotation is reduced to zero.'

'That means till Kerr turns into Schwarzschild.'

'Exactly. Then there is no more rotational energy stored in the black hole. And there is no longer an ergosphere either, as the stationary limit and the event horizon would have coalesced into one. Kerr has turned into Schwarzschild now.'

'How does one realize this process in practice, George?'



'Let me show you a cartoon, Alfie, that shows you one possibility.'

George rummaged through the pile of photocopies lying on the table and brought out a cartoon. It depicted a rather weak man carrying a dumb bell and falling into the ergosphere; throwing the dumb bell into the event horizon and emerging as a strong man, having been energized by the black hole!

'Is this the only possible mechanism for energy extraction, George?' I was quite amused by the cartoon.

'Maybe, maybe,' laughed George. 'Seriously, Alfie, soon after Penrose's discovery, there was a lot of excitement, as though all our energy needs would be solved just by catching hold of a rotating black hole and exploiting it. Hypothetical mechanisms were proposed that would eject garbage into the ergosphere and get out pure energy in return. There were even newspaper articles talking about the superpowers fighting over the ownership of rotating black holes! But it is not all that simple you know. The Penrose process requires some stringent conditions to be satisfied. For instance, the trajectories of the incoming object and the two fragments have to be fine-tuned if the outgoing piece is to carry more energy than the incoming projectile. Much too much to ask for.'

'You mean to say that nature throws away such a nice process, without making use of it?' This was a bit disappointing.

'Well, this process may operate in astrophysical contexts involving matter streaming into the black hole, but may not be all that effective. But in principle at least the Penrose process is quite fascinating.'

'All right, nature may not believe in the principle that whatever is not forbidden is mandatory,' I commented. 'You said that a particle falling into the horizon in a direction opposite to its rotation would slow it down.'

'That is right.'

'Suppose you throw in a particle co-rotating with the black hole. Wouldn't that speed it up?'

'Sure, it increases the angular momentum of the black hole.'

'Now if you keep spinning up the black hole faster and faster, wouldn't it break apart like a liquid drop that ruptures due to excessive centrifugal force?'

'Nice question, Alfie,' remarked George. 'First of all, the horizon exists only if the angular momentum per unit mass, which we called *a*, is less than or equal to the mass M. In practice, we replace M by *m* which, as with Schwarzschild, is obtained by multiplying the mass by the Newtonian gravitational constant and dividing it by the square of the speed of light. When *a* and *m* are equal, the black hole is termed *extremal* with some special properties. We mentioned matter streaming into a black hole from a companion star forming an accretion disk, right? Now, the matter co-rotating with the black hole can spin it up until it tends to become an extremal black hole. This can be astrophysically important as we shall see later on. Coming back to your question, if you start hitting the black hole with co-rotating particles, its angular momentum will keep increasing, no doubt. But so will its mass.'

'Sorry to interrupt you, George. What if we shoot co-rotating photons into the black hole? After all, photons carry angular momentum but have no mass.'

'Clever, Alfie,' smiled George. 'But photons have energy and don't forget energy *is* mass. Also the rotational energy itself contributes to the mass. In any event, one can show that once the black hole or the event horizon has formed, you cannot destroy it. We will discuss this later on in the context of black hole thermodynamics.'

'Agreed. Suppose, George, you had a star rotating rapidly enough to have this parameter a of yours larger than the mass m. Suppose again this star collapsed after exhausting its nuclear fuel retaining the values of a and m. Then what?'

'I wish the students in my class would ask questions like that,' said George, which made me quite happy. 'Fine, let us consider the collapse of a star with a greater than m. In that case, no event horizon would be formed. All along in our discussion so far, Alfie, we have shied away from the beast that lurks in the Kerr spacetime, namely the singularity. As in the case of the Schwarzschild spacetime, so too in the Kerr spacetime there exists a singularity. If it were hidden within the event horizon, the outside world would be blissfully ignorant of its existence since no signal, no information can come out from within the event horizon. But, now, if no event horizon were to be formed, the singularity is exposed to the outside world in all its malevolent manifestation. It is now called a *naked singularity*.'

'Obscene! But why do you keep calling it names – beastly, monstrous, malevolent and what not? Very insulting you know.'

'I will tell you why. To begin with, at the singularity density, spacetime curvature, and all else would be infinite. Or at least unimaginably high, even if some unknown quantum effects have arrested the collapse. If the singularity is clothed properly like a gentleman, wrapped up in the cloak of the event horizon, it cannot harm you. But if it were naked, its behaviour would be unpredictable since all equations break down in its vicinity. Things could come flying at you from the singularity without warning. It could throw a chair at you for all we know. No one likes a singularity, especially if it is naked. Beware!'

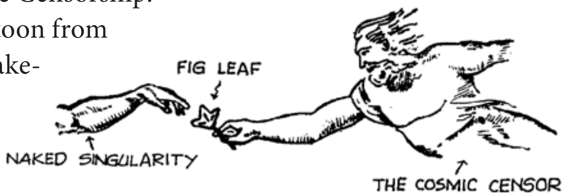
'Then how do you protect yourself from this nude nightmare?' I couldn't help laughing. The whole thing sounded like a Jabberwockian jest. Perhaps it was the way George had described the naked singularity, which, I was sure, was a serious theoretical problem.

'How do we protect ourselves from the naked singularity? By proclaiming that the naked singularity does not, must not, and cannot exist,' declared George. 'Roger Penrose made a conjecture that gravitational collapse could never lead to the formation of a naked singularity, that an event horizon would inevitably cover it up. Even in the case of spherical collapse, in principle, an event horizon need not result. But the conjecture says that it must. Similarly, when the collapsing star is rotating with a greater than mass m it must somehow get rid of the excess angular momentum, say by ejecting layers of spinning matter, so that an event horizon *is* produced. This is known as the Cosmic Censorship conjecture. The Cosmic Censor rules out nudity.'

'Has this conjecture been proved or disproved by theoretical calculations?'

'Well, people have tried to produce scenarios in which a naked singularity arises as an end product of gravitational collapse of all sorts of matter, with all sorts of initial conditions, with some success. But there are still serious questions regarding their existence, including their stability. Let me show you a cartoon about this idea of Cosmic Censorship.'

George pulled out another cartoon from the stack on the table. It was a take-off of Michelangelo's famous painting of God creating Adam, who is obviously naked, God's finger almost touching Adam's. In the cartoon, the Creator had been replaced by the Cosmic Censor offering a fig leaf, namely the event horizon, to the naked singularity.



'Poor Michelangelo!' remarked George as he unscrewed the cap of the thermos flask and peered inside. 'Ah, just enough left for a refill each,' he said and poured the still hot liquid into our cups. There was a cookie left for each of us as well.

'Let us get back to matter falling into the rotating black hole, George,' I resumed our discussion. 'Or the rotating star collapsing and creating the black hole. I suppose the picture is the same as before. I mean whereas the matter crosses the event horizon in finite time, it appears to take forever to reach the horizon as far as a distant observer is concerned.'

'You are perfectly right,' said George.

'Then again there is this tidal force stretching out the hapless astronomer who happens to fall in.'

'True enough.'

'Now of course not only is he drawn out into spaghetti, but the resulting pasta is also twisted around as one does with a fork and spoon. As for the tomato sauce….' I couldn't continue my description of the fate of the unfortunate astronomer as George stopped me.

'Please, Alfie, I won't be able to eat at Bruno's if you go on like this,' protested George wrinkling his nose. 'Confine yourself to ordinary matter falling into the black hole, not humans.'

'All right, what happens to the matter after crossing the event horizon? It gets crushed out of existence by the singularity, I guess.'

'Yes and no,' said George enigmatically.

'What do you mean, yes and no?' I asked. 'Don't tell me that the quantum effects turn the matter into the Schrödinger cat, half dead and half alive like a zombie.'

'No, no, nothing like that, no quantum weirdness, I assure you,' said George. 'Let me explain. In the case of the Schwarzschild spacetime the singularity was a point in space. Inevitably the falling matter hits it and gets crushed. Within the Kerr black hole, as a result of the rotation, the singularity is not a point but a ring. Matter that hits it will be crushed up no doubt. But one can fall through the ring, like a circus dancer through a hoop, and escape the dreadful fate of being obliterated.'

'That is interesting. You elude the clutches of certain death by going back and forth through the ring singularity then?'

George paused for a moment looking me straight in the eye and announced dramatically, 'No, when you fall through the ring singularity, you emerge into another universe!'

'Sounds crazy to me,' I said, baffled by George's statement.

'Perhaps it is,' agreed George. 'It is a mathematical quirk. This takes a bit of explaining. Do you remember the Kruskal representation of the Schwarzschild spacetime we mentioned?'

'Yes, I do. In the Kruskal coordinates there is nothing pathological at the horizon. But the singularity at the origin remains singular.'

'In addition, something else rather unusual happens. As was to be expected, you have the whole spacetime containing the singularity and the event horizon as well as the region outside of them. You can consider this as your universe, so to speak, if you ignore all else around you. But now attached to this is an exactly time-reversed replica of the original spacetime. The replica contains all the features of the black-hole spacetime, the outer region, the horizon and the singularity. In other words, the Kruskal map of the Schwarzschild spacetime is actually a composite of two universes.'

'I see. How does the time reversal come into the picture then?'

'Good question. Take for instance the trajectory of a particle falling into the black hole. It starts from some point far away from the black hole, crosses the event horizon, and finally hits the singularity. Now if you reverse the time, exactly the opposite sequence should follow for the time-reversed trajectory.'

'Wait a minute. This trajectory starts off from the singularity, crosses the event horizon and emerges to the outer region. All this happens in the time-reversed replica of course. This is crazy. I thought the event horizon was a one-way membrane where things can only fall in but cannot come out.'

'It is a one-way membrane all right, which means things can cross it in only one direction. In the black hole case, particles fall in but cannot come out. In the time- reversed counterpart, particles can come out but cannot fall in. Matter can explode from the singularity just as a star collapsed into the black hole. This twin sibling of the black hole has a name.'

'What is that?'

'The *white hole*.'

'Ah, that is what it is! I had heard about the white hole, but didn't know what exactly it was. Do white holes exist?'

'In mathematics, yes. In nature, most probably not. You see there is a natural scenario for the formation of a black hole via gravitational collapse of a star. But there is no such mechanism for the creation of a white hole. Only God, in his infinite wisdom, could have made white holes when He created the universe. If so, we cannot tell when they might explode. Moreover, some theoretical calculations indicate that they are unstable. Therefore, even if they had existed once upon a time, they can no longer be found in nature.'

'All right. Our universe is attached to that of the white hole. Can we not visit the white hole half from our part of the spacetime?'

'Fortunately or unfortunately, no, nothing can cross over into the white hole region from our own, neither material particles nor light rays. Another thing one can deduce is that if you represent the collapse of a star to form a black hole, the material of the star would completely obliterate the white-hole spacetime. So when the black-hole spacetime is created, its white-hole counterpart becomes nonexistent at the same time.'

'In other words, mathematics proposes and physics disposes.'

'That is exactly what happens,' acquiesced George.

'Now, how does all this relate to the Kerr spacetime?'

'I was coming to that. If you do the same thing to Kerr as Kruskal did to Schwarzschild, you will get not two connected charts of spacetime, but an infinite number of maps or universes. It is quite complicated. And if you fall through the Kerr ring singularity, you could emerge in one of those universes.'

'Which would be exactly like the one you started from?'

'Not necessarily. In the course of your journey, you could have even travelled back in time. The universe you have entered could very well be your past. You may even meet yourself as a younger person there. You could impart to your younger self some wisdom arising from your experience in this world. Judging from what I know of you, you will probably end up corrupting your younger self even more than he is, or was, or will be, or whatever. But some say their theoretical calculations show that although you can see your younger self you cannot influence him. So he will end up being what you are anyway. Bad enough if you ask me.' George chuckled heartily.

'All these personal snide remarks apart, do you want me to believe all this? Do *you* believe all this?'

'Frankly, no!' declared George without hesitation. 'All this is interesting mathematics. But I think, and so do many, that physical processes like gravitational collapse cover up all those charts of the Kerr spacetime just as it happens in the case of the Schwarzschild-Kruskal spacetime. Again, to quote you for once, hopefully mathematics proposes and physics disposes.'

'I have one or two questions, George,' I said hesitantly.

'Of course, you have an inexhaustible supply of them,' said George with his unruffled patience. 'What is it then?'

'Well, in the case of the Schwarzschild spacetime, you described the circular orbits around the black hole. What happens with Kerr?'

'Circular orbits in the equatorial plane of the Kerr black hole have been studied in great detail, Alfie,' answered George. 'There can be orbits that follow the direction of the spin of the black hole, or co-rotating orbits, as well as those that go against the spin, or counter-rotating orbits. There are circular light paths too. One very important factor is that the radius of the horizon is less than that of the Schwarzschild black hole. Consequently, the radius of the innermost stable orbit can also be less than that of the Schwarzschild case. In fact it can be less than $2m$, the radius of the Schwarzschild event horizon of mass M.'

'Is that important?'

'It is quite important in the detection of black holes, Alfie. Suppose you have caught a black hole of mass M. If you find out that some celestial object is orbiting it at a distance of less than $2m$, then you have pinned down a rotating Kerr black hole. Isn't that important?'

This was amazing. You find a black hole light years away. Then just by observing some object going around it, you decide whether the black hole is rotating or not.

I think George sensed my astonishment. He asked me with a smile, 'What is your next question, Alfie?'

'You talked about the stability of the Schwarzschild black hole and the gravitational waves in its spacetime. Have these things been worked out for Kerr?'

'Oh, yes, but the calculations are much more complicated,' answered George. 'There are some small technical details lacking in the proof of stability. But we may confidently assume that the Kerr black hole is stable, so we can continue to talk about it unhindered by existential doubts. Then again, gravitational waves have also been studied in great detail. One important thing, the quasi-normal modes now carry information about both the mass and the angular momentum of the black hole. Another interesting effect is the super-radiance. This is the gravitational wave counterpart of the Penrose process, Alfie. You can send a wave of some definite frequencies into the ergosphere and get back a wave carrying more energy than what you sent in.'

'One more question, George.'

'Alfie, earlier you said one or two questions. This is the third one. I am keeping count of your queries you know. All right, what is it?'

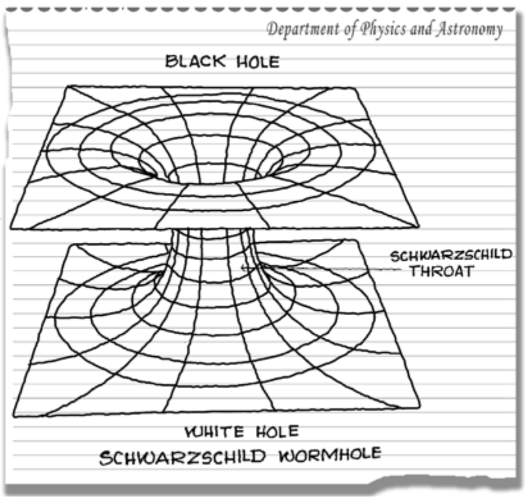
'I have come across the term *wormhole*. Could you tell me what it is?' I ventured.

George took off his spectacles and put them back again after pinching the bridge of his nose for a moment or two. I ardently hoped that I was not taxing him too much with my questions.

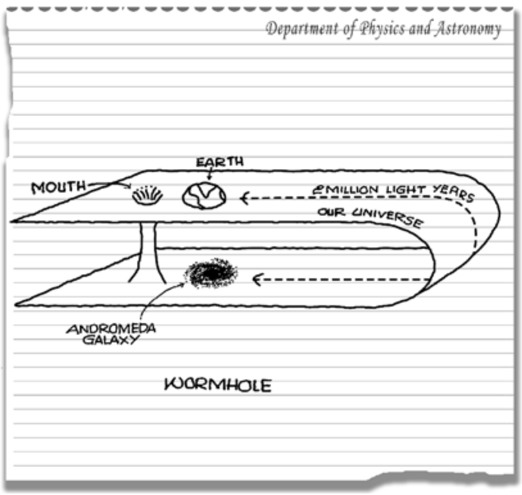
'Ah, you have opened a can of worms there,' began George. 'I shall try to give you just the flavour of the topic without going into details. The whole subject and the term took shape in the nineteen-sixties. We have seen what the pair black hole and the white hole mean, haven't we?'

'Oh, yes. You explained them just now,' I answered.

'We said that we cannot go from one to the other by normal means like light rays or particle trajectories, didn't we? Now, there was speculation regarding the possibility of joining the black hole spacetime and that of the white hole by a sort of tunnel-like structure. Here, let me draw a schematic diagram for you.



You have two mouths, as they are called, one in each of the two spacetimes, and a throat at the Schwarzschild radius. The inter-connecting tunnel was christened a *wormhole*. It so happens that this wormhole is time-dependent. And it was realized that the throat pinches off, not allowing anything to pass between the two holes.’



‘So all this was a futile exercise then,’ I said.

‘Perhaps, but more recently the idea of a wormhole has been resurrected again,’ continued George. ‘Let me draw a picture of this new incarnation of the wormhole for you. Here our universe is represented by this plain two-dimensional sheet that curves around in a U.’

‘One second, where is this all taking place?’ I had to imagine, or desist from imagining, a four-dimensional spacetime going through this contortion, hadn’t I?

‘Well, all this is supposed to be happening in an imaginary, hypothetical hyperspace. Don’t tax your brain about it, Alfie. Anyway, you have to travel over two million light years to go from the Earth to the galaxy in Andromeda by the normal route. But imagine now, if you will, a wormhole connecting the two points with a length of a few kilometres. Then you can reach Andromeda in a couple of hours maybe.’

‘But you said that a wormhole pinches off. Then how can you travel through this tunnel?’

‘Aha, you keep the wormhole open by injecting into it what is called *exotic material*.’

‘What is that?’ This was getting more complicated than I had expected.

‘It is matter with negative density,’ George answered.

‘Does such exotic material exist in nature? Does a wormhole exist in nature to begin with?’

‘You have to construct a wormhole of this type. It does not exist in nature. As for the exotic material, that does not exist either. Some super-intelligent civilization, probably far in the future, is supposed to do all this.’

‘All right, even then if you can reach Andromeda in a couple of hours, wouldn’t you be travelling faster than light? Wouldn’t that mean you could go backwards in time? Which would create the well-known paradox of being able to shoot one's own grandpa so one is not born to begin with.'

'Everything you are saying is true,' affirmed George. 'Those who take the wormhole seriously hope that quantum gravity will save the situation. They believe that the past, present, and the future will all be taken care of properly without any contradictions.'

'But is there such a theory of quantum gravity?'

'No,' George shook his head.

'That means you are trying to explain the mysterious by the nonexistent.'

'Not me, Alfie, I am not trying to explain anything,' shrugged George. 'There is also the view that a reasonable theory of quantum gravity should not allow the existence of wormholes in the first place.'

'Well, in the absence of any possible quantum remedy, the wormhole does lead to the grandfather paradox then. All this sounds like science fiction, if you ask me,' I remarked.

'Believe it or not, the whole field was opened up by science fiction in the first place.' This was quite surprising.

'From what you have told me, it will probably remain science fiction,' I remarked.

'Well, some people think so,' said George. 'On the other hand, there are others who take wormholes quite seriously.'

George thought for a moment and spoke. 'Kurt Gödel thought of time travel too.'

'You mean *the* Kurt Gödel of Gödel's Proof, which shook the world of mathematics?'

'The very same,' confirmed George. 'He discovered a solution to Einstein's field equations which goes under the name of the Gödel universe. It represents a rotating universe. Observations show that our universe is not rotating at all. Still, Gödel's solution is quite important for studying the properties of spacetime in general. Well, this solution admits closed time-like lines or loops in time.'

'What is that?' This was something quite new.

'Suppose you have a circle in space, Alfie,' explained George. 'You can start moving around it and come back to the same point that you started from. Similarly, you can go round the time loop and come back to the past. Gödel took this seriously, and devoted lot of time thinking about the possibility of time travel. Frankly, Alfie, I don't understand why people are so concerned about travelling in time either to the past or to the future.'

'That is what Omar Khayyam says, doesn't he?

Ah, fill the cup: – what boots it to repeat
How Time is slipping underneath our feet:
Unborn tomorrow, and dead yesterday
Why fret about them if today be sweet!'

'Ah, Omar Khayyam, the astronomer-poet, how right he is!' remarked George. 'I wish our own astronomers were poets like him too, Alfie.'

George got up and went over to his desk.

'Alfie, I have to run down the corridor for a minute,' he said, putting together a sheaf of typed pages. 'I have to deliver this grant proposal to the secretary. Today is the deadline you know. It won't take long.'

George hurried out. I walked over to his bookshelf and browsed through his collection of books. There were textbooks, conference proceedings, and volumes specializing in different advanced topics. I thumbed through some of the less technical books and one or two textbooks that looked simple. I put them back deciding that it was enormously more interesting to learn straight from George and clear my doubts into the bargain.

Chapter 14

DYNAMICS OF THE UNIQUE

I didn't have to wait long. George came back within a few minutes.

'Writing these grant proposals is a nuisance, you know. Can't help it. After all, we need our share of bread-and-butter. Don't we?' remarked George. 'Well, where were we?'

'So far, George, you have told me about two kinds of black holes,' I started without any preamble. 'Yesterday it was the non-rotating Schwarzschild, which is spherical in shape. Today you have been telling me about the rotating Kerr, which has a specific spheroidal shape. Now stars in general need not have exactly those shapes, I presume. In principle, I take it that they could look like potatoes and pears, or cabbages and kings. Am I right?'

'I wouldn't go so far as cabbages and kings, Alfie,' laughed George. 'Or for that matter potatoes and pears either. But, yes, stars can differ from perfect spherical shape or even from the Kerr-type spheroids.'

'Well, then, if these stars that have different shapes collapsed, would they result in black holes other than the Schwarzschild and the Kerr?'

'To rephrase your question, Alfie, are the two types of black holes unique, or are there other types differing from the Schwarzschild and the Kerr. An excellent question indeed!' remarked George. He seemed to be quite happy that I had started off on this new track. 'In the very early days of black-hole research, it was assumed, and expected in fact, that black holes could come in all sorts of types and shapes. But it was shown as a rigorous mathematical theorem that there can be one and only one type of black hole that is non-rotating, and whose gravitational field falls off at large distances.'

'Namely the Schwarzschild black hole?' I asked and continued my query. We seemed to be treading on strange grounds now. 'If the collapsing star is non-spherical, even if non-rotating, how can it end up as a spherical black hole?'

'Remember we talked about gravitational radiation,' answered George. 'It is produced by a mass configuration, which is non-spherical and is changing with time. We shall talk about this again when we discuss the detection of black holes. A collapsing non-spherical mass distribution fits this requirement and acts as a source of gravitational radiation. As the radiation is emitted, the asymmetries get smoothed out and the star collapses into a spherical black hole.'

'What about the Kerr black hole then?'

'The uniqueness of the Schwarzschild black hole was a startling result to say the least, Alfie,' answered George. 'But it led to the conjecture that the Kerr black hole must be unique too. That is if you assume that the black hole is time-independent, rotating and its gravitational field diminishes progressively as we go farther from it, then it can be nothing but the Kerr black hole. Many people worked on this problem for a long time, Alfie. Adding bits and pieces to the investigations in this direction before the uniqueness was proved.'

'I can see that this is truly an amazing result, George, to realize that nature allows only two kinds of black holes to exist.'

'You are absolutely right, Alfie. You may start off with stars that are totally different from one another in their constitutions – temperatures, densities, forces acting and many other aspects, totally different in size and shape. But ultimately they can only end up as just two types of black holes that are exact solutions of Einstein's field equations. All the complicated attributes of the original star are washed away, culminating in an entity that is the purest and the simplest manifestation of spacetime curvature. Isn't that incredibly beautiful, Alfie? Do you see why some of us are incurably in love with the black hole?'

I remained silent. I did not have to answer George's questions. I could see how beautiful this result was and I could imagine how George felt about it.

After a few moments of contemplative silence, George continued. 'I must qualify the uniqueness of the black holes a bit. So far we were talking about electrically neutral black holes. As you know, Alfie, matter is, in general, neutral. Stars do not carry any excess electric charge. So when they collapse and turn into black holes, they are either the Schwarzschild or, more likely, the Kerr since all stars rotate. Nevertheless, black holes carrying a net charge can exist in principle.'

'Are they exact solutions of the Einstein's equations too?' I asked.

'Well, let us say they are solutions of the Einstein-Maxwell equations. You have to take into account the energy of the electromagnetic field generated by the charge, in addition to the mass that has collapsed. At the same time, the electromagnetic field must satisfy the Maxwell equations.'

'Seems more complicated than the vacuum black hole solutions to me. But you say such exact solutions do exist.'

'Yes. Quite early in the game Hans Reissner and Gunnar Nordström discovered the charged version of the Schwarzschild solution. It has both mass and charge. It is endowed with a purely radial electric field. There is a limit to the charge you can pack into the black hole though.'

'What happens if you force-feed more charge than the limit? Or if the collapsing matter did carry a charge larger than the limiting value?'

'Then the event horizon won't exist and you are left with a naked singularity.'

'Good heavens, the naked singularity streaks again, this time all charged up! How about the charged version of the Kerr black hole?'

'It is known as the Kerr-Newman black hole, Ezra T. Newman being the one who found the solution sometime after the discovery of the uncharged Kerr spacetime. In this case, the black hole carries mass, angular momentum and charge, three parameters in all.'

'What about the electromagnetic field of this black hole? Or should we say electric field since the black hole has only an electric charge?'

'Strangely enough, Alfie, it *is* electromagnetic field, not just electric field. When a charge revolves in a circle, as in a current loop, a magnetic field is generated, right?'

'Right, I know that.'

'Now the rotation built into the spacetime has the same effect. So a magnetic field is also produced. It is quite an interesting effect.'

'One basic question, George. How do you charge a black hole, at least in principle? In high school, our teacher showed us how to charge an amber rod by stroking it with cat skin. I suppose that a black hole cannot be stroked with a cat skin, let alone a cat.'

'Well, you can try your experiment once you have caught hold of a black hole and a willing cat, I suppose,' commented George with mock seriousness. 'However, normally one thinks of some astrophysical mechanism to do the job. For instance, take an accretion disk around a black hole. There can be charge separation taking place in the accretion disk due to external magnetic fields. And an excess of one kind of charge, positive or negative, may fall into the black hole and charge it. But even if something like this happens, it is expected that the opposite charges hovering around would also be attracted to the black hole and neutralise the original charge. As a result, astrophysicists don't take charged black holes too seriously. But these black holes are quite interesting from a theoretical point of view, Alfie. Similarly there are solutions of black holes immersed in an external magnetic field. But if we are considering isolated black holes whose fields fall off at large distances, then they are endowed with three, and only three, parameters – mass, angular momentum and charge. That is the bottom line of black hole uniqueness.'

I heard voices, approaching along the corridor outside, engaged in animated conversation accompanied by uninhibited laughter. 'Here come the kids, my three graduate students,' announced George, his face lighting up with pleasure.

There was a casual knock on the door, which burst open and in trooped two boys and a girl still talking and laughing.

'Quiet, you guys,' admonished George. 'It seems there was a big sign saying *Talk Softly Please* in Rutherford's lab. I think I shall hang up a sign like that.'

'Sure, sure,' the girl said, 'but that sign had been put up by Rutherford's younger colleagues. They were afraid that Rutherford's booming voice might upset their experiments. We have a similar situation here.' She gave a tinkling laugh.

'All right, have it your way,' George laughed too. 'Let me make the introductions. This is Alfie, the true seeker of knowledge. And, Alfie, this is Paul Thompson. Supposed to be writing his doctoral thesis. Says he can do it in six months, but when he is going to start writing is a mystery.'

Paul was tall and slim, with an aquiline nose, thin lips and a serious countenance. He was dressed a bit more formally than the others.

'And this is Wei-Li Chang. He is from China or *Tien-hua*, Under the Heavens, as he prefers to call his country,' George continued his introductions. 'His first name has been corrupted into William or Bill by the uninitiated.'

Wei-Li was of short, stocky build. He looked quite jolly, with a wide and ready grin.

'But we prefer to call him Wile-E,' the girl added. 'After the famous Wile E. Coyote of the *Road Runner* cartoons.'

'And finally we have here Sunitha from India,' George introduced the girl with obvious pleasure. 'Popularly known as Sunny.'

I thought I had seen her somewhere before. Then I remembered. She was one of the members of the choir that had performed *Miserere* in the University Chapel. She seemed to be full of life, ever ready to give out her characteristic tinkling laughter.

'I am sorry if we interrupted your conversation,' said Paul.

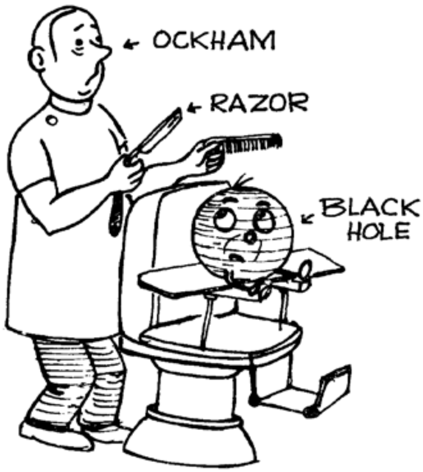
'Not at all,' George assured him. 'Alfie and I have been discussing some black-hole physics. You three can join in too. We had just finished uniqueness, how black holes are characterized by only three parameters – mass, angular momentum and charge.'

'Ah, the no hair theorem!' Paul exclaimed.

'What is that?' I was puzzled.

'Let me explain, Alfie,' said George. 'As we discussed already, when a star collapses to a black hole, all the characteristics of the stellar matter, such as the atomic structure, the attributes of the constituents like protons, neutrons, and electrons, the nuclear forces and so on, are all washed away leaving behind just the three parameters. Now, it was John Wheeler who coined the term *no hair theorem*. According to him, all those complexities of the star are supposed to be like the hair on the head that gives characteristic identity to an individual. This is gone in the case of a black hole. So it has no hair, it is bald.'

'I think that the no hair theorem is the ultimate application of Ockham's Razor,' remarked Sunitha or Sunny.



Raising his eyebrows Paul looked at Sunny and shrugged his shoulders.

Wei-Li looked from one to the other questioningly and asked Paul innocently, 'Who is this Ockham, please? Is he a barber?'

'Ockham or William of Ockham, Wei-Li, was not a barber,' Paul explained patiently. 'He was an English scholiastic philosopher and theologian. He formulated the principle of simplicity or Ockham's Razor as it is called. The principle states that an idea or a theory, which is most preferred, is the simplest one shorn of all unnecessary details.'

Sunny burst out laughing. 'Paul, Wile-E was pulling your leg. As an undergraduate, he had two courses in philosophy and theology. He knows all about Ockham, his razor, and his hair splitting. Wile-E looks straight as a chopstick but he is crooked as noodle. You know that.'

Paul pursed his lips and said seriously, 'A childish prank. I should have known.'

Suppressing his smile, George held up his hand and said, 'Kids, enough of this. Let us get on with the black holes.'

Wei-Li turned to me and queried, 'Has the professor told you about black-hole entropy and temperature? If not ask him, please.'

'Tell me about black-hole entropy and temperature,' I asked George obediently.

'All right, Alfie, the subject of entropy and temperature of the black hole is quite an important one,' he said. 'You know why? It is a topic that connects the past, the present, and the future of black-hole physics. It makes use of all the properties of black holes discovered in the past. Active research related to black-hole entropy is still going on at present. And the results of such investigations may lead us into fundamental areas like quantum gravity in the future.'

George paused, drumming his chin for a moment or two.

'All this started with the study of the dynamics of black holes, you know. It was soon realized that there were striking similarities between black-hole dynamics and conventional thermodynamics' continued George. 'Ah, thermodynamics, there is a wonderful subject for you. Einstein thought so too, and wanted his relativity theory to be an all-embracing one like thermodynamics. We must discuss conventional thermodynamics a bit before considering the case of black holes in this context. As we know, central to it are the concepts underlying energy, temperature, and entropy. Let us talk about this strange and wonderful quantity called *entropy* then. You know about it, don't you?' George asked, turning to me.

'Vaguely, yes,' I answered. 'The word comes from Greek meaning "transformation". But go ahead, George, explain everything in detail.'

'Transformations, yes, that is the keyword,' said George. 'In nature, there are reversible and irreversible transformations involving heat transfer. A familiar example of an irreversible process is the heat transfer from a hot body to a cold one, this cannot happen in the reverse direction.'

'How about reversible processes then?' asked Paul.

'Aha, giving me a cue, eh, Paul?' George smiled. 'If two bodies are at the same temperature, a small amount of heat can flow from one to the other in either direction. This is obviously a reversible heat transfer. These ideas were developed and used by Carnot. He made very significant contributions to thermodynamics, you know.'

'A word about Sadi Carnot,' I supplied the historical background. 'Son of Lazare Carnot who was himself a scientist and a prominent figure in the French Revolution. The son was named after Sadi, the great medieval Persian poet, whom his father admired. Sadi Carnot served in the army for some time, and published a monograph on heat engines. Poor man, he contracted scarlet fever followed by cholera, and died at the early age of thirty-six.'

The three students listened intently in silence, almost with respect, to this unexpected piece of erudition. George laughed and said, 'Don't you ever underestimate our Alfie here. Silent waters run deep. You never know what he knows, nor what he is thinking.'

'I am glad you are telling us all this, Alfie. History makes science come alive,' said George turning to me. 'Carnot's engines, they were theoretical devices intended to maximise efficiency. Carnot thought of the ideal engine in which all processes were reversible. In such an exchange of heat, Carnot found that the ratio of the heat transferred to the temperature was a constant. This quantity he called the *entropy*.'

'Enter entropy amidst irreversible fireworks and irreversible drum rolls,' Sunny announced. 'What happens to entropy in an irreversible process?'

'Another cue, I suppose,' George smiled at Sunny. 'Almost all processes in nature are irreversible. Fire burning, cells dividing, eggs hatching.'

'Or breaking an egg and making Foo Yong ,' Wei-Li added.

'Or egging on the professor to give us a raise in our allowance, which is a futile gedanken eggsperiment,' Sunny put in.

'Which you know is an eggzaduration.' George joined in this crazy exchange, laughing heartily.

'Why do these two have to be so flippant and joke around all the time?' asked Paul looking at George reproachfully.

'Paul, I believe it was the renowned nuclear physicist, Victor Weisskopf, who asked his mentor Niels Bohr exactly the same question,' George answered. 'Everyone at Bohr's Institute in Copenhagen, including Bohr himself, would be joking, laughing, and playing pranks, which annoyed Weisskopf. You know what Bohr told Weisskopf in his own gentle manner? *Victor, in life some things are so serious that all you can do is to laugh at them!*'

'What is so serious about entropy then?' questioned Paul in a challenging tone.

'What is so serious about entropy, Paul?' George raised his eyebrows. 'It *is* a serious business and you know it. In every irreversible process the entropy goes up. The total entropy of any closed system keeps increasing as irreversible changes take place. This way the entropy of the entire universe is tending towards a maximum. This in fact defines the arrow of time. We age because of entropy. If this is not serious, especially at my age, I don't know what is. I am sure you know this, Alfie. The fact that entropy increases in a closed system spells out the second law of thermodynamics.'

'Oh, yes,' I answered. 'C.P. Snow once said that not knowing the second law of thermodynamics is like never having read Shakespeare.'

'How true,' said George, 'Well, to press on, entropy is also connected to order, or shall we say to disorder, and information content. Why don't we talk about these aspects of entropy? How about you three? Why should I do all the work!'

'Fine, let me begin,' volunteered Paul who was warming up to the discussion. 'Consider, for example, two adjoining chambers, one of which contains some gas. The individual molecules of the gas would be moving around assuming a certain number of positions, thereby having some disorder. Now, make an opening in the partition between the two chambers allowing the gas to expand. The volume of the gas has now increased and so has the number of positions available for the molecules to occupy. Naturally, the disorder increases too, as the molecules move around among these available positions. This is an irreversible process, you know, since you cannot make the gas molecules return to their original chamber. Entropy goes up too, since the process is irreversible. So, you see, entropy increase is correlated with increase in disorder.'

'All this is like what the Roman poet Horace wrote: *A word once let out of the cage cannot be whistled back again*,' I remarked. 'A word, a rumour, let out of its cage can create turmoil.'

'Alfie, you are really fond of human analogies for physical phenomena, aren't you?' commented George.

'Oh, we love human analogies,' said Sunny.

'All right, let us get back to real entropy,' said George. 'Order also implies more available information like a sentence made up of well-arranged letters of the alphabet. Mix up the letters and this available information is lost. It works the other way around too.'

'Like a monkey typing out a Shakespearean play in a million years bringing order,' added Wei-Li.

'But not a scientific paper though,' commented Sunny. 'Monkeys are too intelligent for that. Let me give a familiar example for all this entropy business. Take my desk. It is well organized with the papers neatly stacked, books placed between bookends, pens and pencils arranged in the holder. High order, low entropy. Wile-E's desk – things thrown around at random. We can have lots of arrangements of the junk to make the same mess. Total disorder, high entropy. Terrible!'

'Hold it, Sunny Girl,' Wei-Li interrupted her. 'May I refer you to the *Feynman Lectures on Physics, Volume One*. In the section on entropy, Feynman clearly says that it is not a question of pleasant order or unpleasant disorder. So there!'

'I protest,' Sunny said.

'What is she protesting about?' asked George.

'Oh, ignore her, Professor,' answered Wei-Li. 'I think it is about gender equality. She says women feel that names like Feynman with the word *man* built into them are male chauvinistic. It should be Feynperson according to them.'

'I protest,' Sunny repeated.

'*The lady doth protest too much*,' quoted Wei-Li and added, 'I don't know whether Sunny qualifies to be called a lady though.'

'What are you protesting against now, Sunny?' asked George.

'The name Feynperson embodies a sneaky, second-order male chauvinism,' replied Sunny. 'The word *person* has built into it the word *son* which is again male. It ought to be Feynperchild!'

'That is a good one, Sunny,' said Paul laughing loudly to our surprise. 'Feynperchild! That is really good, Sunny.'

'The entropy in this room is really increasing beyond control,' George said shaking his head. 'Sunny, continue your analogy if you must.'

'All right, our desks and entropy,' Sunny continued. 'By the way, Paul keeps everything in filing cabinets. His desk is empty. Zero entropy.'

'Which means it's temperature is absolute zero, which is when entropy is zero,' Wei-Li put in. 'Desk as cold as the user.'

'I refuse to take cognisance of that remark,' Paul told Wei-Li with mock dignity, which was not convincing at all. Paul was obviously enjoying the conversation. Well, so was I.

'Let me continue,' Sunny went on. 'We write papers, don't we? Highly ordered documents with low entropy containing a lot of available information. When we hand our papers to the professor, he tosses them onto the huge pile on his desk, which forms a subsystem with unimaginably high entropy. The process is irreversible. We never get back our papers. And all the available information is lost!'

'Not before I have read the papers, Sunny,' retorted George. 'Information lost is knowledge gained.'

'*Where is the wisdom we have lost in knowledge? Where is the knowledge we have lost in information?*' I quoted.

'Who wrote that?' George asked with interest.

'T. S. Eliot,' I answered.

'I agree with him perfectly, but he puts it so beautifully as all your poets do, Alfie,' acknowledged George.

'All the information you people have given me is absolutely fascinating,' I said with genuine appreciation. 'But along with information we seem to have lost sight of the black hole too.'

'Oh, no, Alfie, we have not lost sight of the black hole at all,' assured George. 'The preamble was necessary since often we forget the basics from which we build our new theories. Black-hole thermodynamics offers rules and principles that dictate how black holes behave and interact. Like the Penrose process, it imparts, in a way, dynamics to the black holes. As I told you earlier, one spoke of black-hole dynamics, which was eventually turned into black-hole thermodynamics when the close analogy was established.'

'So. A black hole is not an idle Venus's Flytrap after all, doing nothing but gobbling up insects that fall into it,' Wei-Li commented.

'Mars's Flytrap, Wile-E, not Venus's!' Sunny corrected.

'All right, let us get the ingredients that go into the dynamics before we cook up the thermodynamics,' began George. 'As we know, the black hole keeps swallowing up matter. In this process, don't forget, it is getting fatter which *is* a dynamical process.'

'How do you measure the fatness of the black hole, George?' I asked.

'Simple, Alfie, compute the area of the horizon,' answered George. 'In the case of the Schwarzschild black hole it is just the area of a sphere, which is proportional to the square of its radius, $2m$. So the surface area is proportional to the square of the mass, which keeps increasing as the black hole eats up matter. In the Kerr case the formula for the area contains both mass and angular momentum, but it too increases as the black hole dines on matter and energy. For instance, this happens in the Penrose process. Since nothing can come out of the black hole, the area must either remain constant or must necessarily increase. Does that remind us of a thermodynamic quantity which too never diminishes?'

'Entropy!' exclaimed Wei-Li.

'That is what Jacob Bekenstein discovered in the early nineteen-seventies. Yes, it is but an analogy, a clue,' said George. 'But the game is afoot, Watson!'

'Not Watson, George, say Watchild,' remarked Paul looking at Sunny and laughed contentedly at his own comment.

'I stand corrected, Paul. Let us follow the track of the beast then,' continued George. 'Now that we have discovered that the area of a black hole behaves like entropy, we need the analogue of temperature, which goes hand in hand with entropy. Who will explain this?'

'I will, I will!' both Sunny and Wei-Li cried simultaneously.

'All right, both of you go at it, without creating confusion,' said George.

'Let us take a gas in a jar,' began Sunny. 'It has some volume, pressure, and temperature.'

'And entropy since the gas molecules are whizzing around,' added Wei-Li.

'Now give the gas a little bit of heat which is nothing but energy,' continued Sunny. 'Now here comes the important thing. The gas has internal energy because of the motion of the molecules that are zooming around. The heat we gave increases this internal energy.'

'Which means the chaotic motion of the molecules has increased,' said Wei-Li.

'Which means the entropy of the gas has increased. And now for the punch line. The increase in the internal energy of the gas turns out to be equal to the product of the temperature and the increase in the entropy. So, entropy and temperature go hand in hand. The explanation is complete,' concluded Sunny.

'Now, Alfie, the black hole case is exactly like this,' George took over. 'Suppose we increase the mass of the black hole by injecting some particles or radiation into it. The increment in the black-hole mass is like the heat or the energy you imparted to the gas. This increment can be shown to be directly proportional to the increase in the area, which is the analogue of entropy. Therefore, the coefficient multiplying the increment in the area is the equivalent of the temperature in the case of a gas, which Sunny and Wei-Li described just now. This coefficient turns out to be what is known as the *surface gravity* of the black hole. For the Schwarzschild black hole, this has the same expression as that of the Newtonian gravitational field computed at the radius of the horizon. But, as we discussed at length, Alfie, the Newtonian gravitational field is not a physical quantity you can measure at the horizon. For the Kerr black hole, the formula for the surface gravity is a little more complicated, as was the area. It involves both mass and angular momentum of the black hole. Anyway, we have now the analogues of both entropy and temperature of the black hole. Isn't that nice?'

It was quite appealing in fact.

'Yes, it is indeed,' I agreed. 'So we have the analogues of temperature and entropy of the black hole. How does the thermodynamics of the black hole emerge out of them?'

'I was coming to that, Alfie,' answered George. 'First, let us note something remarkable about surface gravity, the analogue of temperature. In the case of the Schwarzschild black hole, surface gravity is simply proportional to the mass divided by the square of the radius of the event horizon or, in other words, inversely proportional to the mass. Obviously, it is constant over the spherical event horizon. Now, as I mentioned just now, the surface gravity of the Kerr black hole has a little more complicated expression, involving both the mass and the angular momentum. Remember the event horizon is no longer a sphere, but is something like a spheroid in shape. Nevertheless, here is the astonishing fact. The surface gravity is still a constant over the event horizon in spite of its non-spherical shape. This is unlike the case of the Earth for instance. The surface gravity varies from place to place because of the Earth's shape. It is greater at the poles than at the equator. This constancy of surface gravity is maintained even when black holes interact and come to equilibrium. What should this remind us of?'

'The zeroth law of thermodynamics,' chimed in Sunny. 'It is my favourite law, since zero was discovered in our country, you know. The law states that all parts of a system in thermal equilibrium have the same temperature.'

'Explain please,' interjected Wei-Li.

'All right, as an example take bath water,' Sunny elaborated. 'Imagine Archimedes wants to take a bath. He opens both hot and coldwater taps—probably made of solid gold. The system, namely the bathwater, is not in thermal equilibrium to begin with. Different parts have different temperatures. Archimedes knows this and waits. Hot and cold water get mixed up and the bathwater is at the same temperature all over. And Archimedes takes a bath.'

'No, he does not,' commented Wei-Li. 'He runs out of the bathroom shouting "*Eureka*", which in ancient Greek meant "the bathwater is too hot".'

'Crazy!' exclaimed Paul.

'Oh, these kids are incorrigible,' George shook his head smiling, and continued with black-hole thermodynamics. 'Again, let us take some process involving the interaction of black holes as before, like their coalescence. In such a process gravitational radiation would be emitted which would carry away energy. Now in all such events, the total mass and energy would be conserved.'

'Ah, that is like the first law of thermodynamics' it was Wei-Li's turn to declare. 'The law tells us that in all physical processes, the total amount of energy is conserved. Energy may be exchanged or converted from one form to another, like heat to mechanical energy as in the steam engine, but the total cannot either diminish or increase.'

'Now we come to the second law of black-hole thermodynamics,' announced George. 'If you take a single black hole, we know that the area must increase as it consumes mass and energy. But the fantastic fact is that even when black holes interact, such as two of them coalescing, the resulting area will never diminish. This is exactly like the second law of conventional thermodynamics.'

'Let us not forget the third law,' put in Paul. 'As we all know, temperature can be measured using different scales. Each one has its own zero. There is the Celsius scale, for instance, which takes the melting point of ice as the zero degree.'

'Just a curious historical fact again,' I interjected. 'A French astronomer named Joachim Delance had proposed the melting point of butter as the zero point.'

'Ah, now I understand,' exclaimed Wei-Li. 'That is where the expression "butter wouldn't melt in the mouth" came from.'

'Don't be ridiculous, Wei-Li. I fail to see the connection,' Paul said sternly and continued. 'Now for all thermodynamical purposes one uses the Kelvin scale. The so-called absolute zero of temperature is the zero on the Kelvin scale, which is equivalent to minus 273.16 degrees on the Celsius scale. I am sure all this is well known. I am just repeating it for the sake of completeness –as we write in our papers to justify redundancies. Now for the third law of thermodynamics. The law states that it is impossible to bring the temperature of a system to absolute zero in a finite number of operations.'

'Paul, why don't you continue and tell us how this translates into the third law of black-hole thermodynamics?' George urged Paul.

'Why not? That is my area, no pun intended,' smiled Paul. 'First the simpler case of the Schwarzschild black hole. As we saw just now, the temperature, or the surface gravity, has for its formula the Newtonian gravitational field at the horizon. This is proportional to the reciprocal of the mass, as we saw. You cannot increase the mass to an infinite value in a finite number of operations, feeding the black hole finite amounts of energy in each operation. Therefore you cannot reduce the temperature to zero either. Now this applies to the Kerr black hole also. In addition, the surface gravity over the Kerr horizon depends directly on the mass m minus the angular momentum per unit mass a of the black hole. Therefore surface gravity can also go to zero if the angular momentum a can be made to be equal to the mass m.'

'Ah, George and I discussed this,' I said. 'We saw that this could not be achieved once we have a horizon already with a less than m.'

'Exactly. Surface gravity, which is like temperature, cannot be reduced to zero in a finite sequence of operations, which is the analogue of the third law,' commented Paul.

'There you are, Alfie. We have all the three laws of black-hole thermodynamics,' George concluded with relish.

This was amazing. Here was thermodynamics, developed over centuries, which embraced all physical processes through its extraordinarily simple laws. And now we have black holes, the offspring of general relativity, with no apparent direct connection to conventional thermodynamics. Yet, their dynamics follow exactly the same laws. What fundamental principles dictated this? I wondered. Well, I had some doubts still to be cleared at a more mundane level.

'George, you have been saying that the surface gravity and the area of a black hole are *like* temperature and entropy,' I said. 'But I have come across the expression black-hole temperature. What does that mean? How do you measure the temperature of a black hole? You couldn't possibly stick in a thermometer into the black hole, could you?'

'Well, that seems to be a bit impractical, Alfie,' said George dryly. 'There are other ways and means of determining temperature of an object without the direct use of a measuring device. If you heat a material body, you can infer its temperature from the spectrum of the radiation emitted by it. By the way, it was Max Planck who derived the correct law connecting the intensity and the frequency of this radiation for the first time, introducing his quantum hypothesis.'

'So, how do we infer the temperature from the spectrum?' I rephrased my question.

'If you look at the intensity of radiation it shows a maximum, which is a characteristic of the temperature of the source, Alfie,' explained George. 'The higher the temperature of the source, the shorter the characteristic wavelength corresponding to the maximum intensity of the emitted radiation. Or equivalently, the greater the frequency. So this way, you can infer the temperature of the emitter by examining the spectrum. For instance, the Sun's outer region is at around six thousand Kelvin. And the spectrum of the radiation coming from it peaks in the yellow. If you poke a thermometer into the Sun's atmosphere, the thermometer would evaporate. You wouldn't want to waste money on a thermometer doing that, would you? Instead, you determine the temperature of the Sun from the spectrum of its radiation. Similarly, needless to say, if you stick in a thermometer into a black hole, the thermometer would be swallowed up. Therefore you must follow similar procedure as you did for the Sun.'

'Wait a minute, George,' I said. 'The Sun radiates. Even I know that. So you can find out its temperature from the spectrum of its radiation. But, what about the black hole? Surely, a black hole doesn't radiate!'

'Aha, that is the most astonishing part of our story,' beamed George. 'The black hole does radiate.'

'Oh, come on, George,' I protested. 'You want me to believe that? Nothing can come out of a black hole. You explained why in great detail.'

'I can't blame you, Alfie. When the fact that a black hole radiates was first announced, most physicists were incredulous too,' George told me. 'But it is true. Let me explain.'

George paused as if preparing for launching into a new topic, while the students waited expectantly. Again, I was sure they knew the facts, but were eager to find out how George would put across the ideas. And, of course, I was eager to know about this unbelievable phenomenon.

'In the nineteen-seventies, Stephen Hawking discovered this totally unexpected effect,' began George. 'You know that normally elementary-particle physics is done in flat spacetime using what is known as the quantum field theory. The theory deals with quantum effects such as the production of particles in electromagnetic fields and so on. Normally particle physicists use a flat spacetime as the background for studying these quantum phenomena. This means that one is not including the effect of gravity. Now you can take into account the influence of gravitation by carrying out these calculations in the background of curved spacetime, such as the Schwarzschild spacetime, for instance.'

'George, you told me that there exists no theory of quantum gravity,' I pointed out. 'Then how can you think of quantum effects in a gravitational field?'

'You are right, Alfie, no one has been able to quantize gravitation,' averred George. 'Quantum fields superposed on curved spacetimes is not a true marriage of quantum theory and gravity.'

'Ah, then it is just a courtship between the two,' I suggested.

'Maybe, but the formalism does give reliable results,' said George. 'So Hawking worked out the possible particle creation in the gravitational field of the black hole. And amazingly enough, he found that the black hole does emit elementary particles and photons. What is more, their spectrum was exactly that of the radiation emitted by a heated body.'

'Which meant that the spectrum had a characteristic temperature,' I drew the obvious conclusion. But this was getting really intriguing.

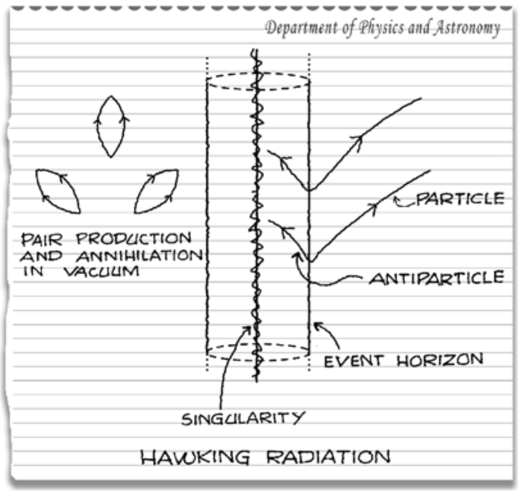
'Oh, yes, and that temperature turned out to be proportional to – hold your breath, Alfie – the surface gravity of the black hole!' declared George.

'Again just proportional to?' I asked.

'No, this time around, the proportionality constant also dropped out of the calculation,' answered George. 'This constant was made up of two fundamental constants, namely the Boltzmann constant, which enters into conventional thermodynamics, and Planck's constant which characterizes all quantum phenomena. This meant that the black-hole temperature and its entropy could be expressed exactly in terms of the surface gravity and the area respectively.'

'All this sounds truly fantastic, George,' I remarked. 'But can you give me an idea of the mechanism that leads to this Hawking radiation?'

George pondered for a moment before replying. 'All right, Alfie, this takes some explanation. You must remember the process involves quantum field theory. We have not discussed it in detail, but I shall tell you the bit we need. I am sure you know enough about elementary particles like the electron, proton and so on. For every elementary particle, there exists an antiparticle. For instance, the positron is the antiparticle of the electron and carries a positive charge. Similarly, we have the antiproton with negative charge. When a particle and its antiparticle come together, they annihilate each other giving rise to radiation. Likewise, radiation can simultaneously create a particle and its antiparticle. These processes conserve the total energy involved. In the flat spacetime, even in vacuum you have the creation of particles and antiparticles going on. Since the vacuum has zero energy, one of them must have negative energy to balance the positive energy of the other. You do not observe this negative energy since the two annihilate each other on extremely short time-scales. Now let us see how this process is modified near the event horizon in the Schwarzschild spacetime. Hawking's original calculation was done for Schwarzschild in the first place anyway. According to quantum theory, the exact location of any event is indeterminate. This is due to Werner Heisenberg's uncertainty principle, which stipulates that both the position and the momentum of a particle cannot be given exactly. Suppose now, out of the vacuum, a particle and an anti-particle pair is created with one of them outside the horizon and the other inside of it, the two being very close to each other. The one outside has positive energy and escapes to infinity. Its counterpart possesses something like negative energy. It is not exactly energy in the conventional sense, due to time changing its nature at the horizon. This is a subtle effect, Alfie, and we need not go into the details. In any case, there is energy balance in the pair production. The component created inside the horizon falls into the singularity and never comes out. So there is no difficulty in its having negative energy – "energy" in quotes. Finally, the particles created outside the horizon stream out as Hawking radiation. I hope I have given you some idea of what is happening with this strange phenomenon, Alfie.'



'Certainly, George,' I affirmed. 'I didn't expect anything more without knowing the full theory behind all this. But tell me, what happens to the black hole itself in all this?'

'Ah, the picture gets stranger still,' replied George. 'Due to the particle or the antiparticle falling inside the event horizon carrying the negative equivalent of energy, the mass of the black hole diminishes. So, as the particle production proceeds, the mass of the black hole keeps going down. Or in other words, the radiating black hole evaporates. Remember the temperature of the black hole is directly proportional to its surface gravity, which in turn is inversely proportional to the mass of the black hole. Therefore, as the mass decreases due to particle creation, the temperature keeps shooting up and the evaporation rate steadily increases until the black hole explodes in a burst of particles and goes out of existence.'

'George, I think you have cornered yourself into an ontological conundrum,' I said. 'If the black hole evaporates and goes out in a blaze of particles of its own creation, then how can it exist at all in nature?' I was really puzzled.

'Alfie, I have not cornered myself into any kind of drums,' George chuckled. 'We saw that the temperature of a black hole varies as the inverse of its mass, right? The temperature of a black hole of the common-or-garden variety, comparable in mass to our Sun, turns out to be about a ten millionth of a degree. At that kind of temperatures, the black hole hardly radiates at all. Which means you can totally ignore its evaporation. The black hole will continue to exist merrily and you don't have to worry about its ontology or oncology or whatever.'

'The black hole evaporation is of just academic interest then?' I wanted to know.

'Well, if you have a mini black hole weighing say a billion billionth of the mass of the Sun, which would be the size of a proton but with the weight of a mountain, then its temperature would be of the order of a trillion degrees. And it would be spewing out copious amounts of gamma rays and elementary particles. For such a teeny-weeny black hole evaporation would be of deadly importance.'

'Mini black holes?' This was even more puzzling. 'I thought black holes have to be heavier than the neutron star limit, about five solar masses or so. Where do you get these proton size midgets?'

'Well, Alfie, these little black holes are not the end products of stellar evolution,' George clarified. 'They are supposed to be primordial black holes created at the very beginning of the universe by the enormous stresses due to density fluctuations that might have existed then. The hand of God kneading the cosmic clay, you know.'

'How fast do these mini black holes evaporate?'

'Good question. It is easy to calculate the rate of evaporation and the lifetime of an evaporating black hole. This depends on the mass of the primordial black hole. For the mini black holes of the weight I mentioned, it turns out to be some ten billion years.'

'That is more or less the age of the universe, isn't it?'

'You are right. It follows that these primordial black holes must be popping out all over the universe now.'

'Have they been observed?'

'No, some ways of detecting were proposed and those methods did not yield any results. If you ask my opinion, these primordial black holes belong to the realm of pure speculation.'

'One last question, maybe of just academic interest,' I said. 'What happens when a primordial black hole, if it exists, evaporates away. Does it leave behind a naked singularity?'

'Your guess is as good as mine, Alfie,' said George. 'Perhaps anything concerning the singularity will have to take into account quantum effects. That means we need quantum gravity, which we do not have. It is all a mystery, if you ask me.'

'We in India have known this all along. The whole world is *Maya*, nothing but illusion,' remarked Sunny.

'The great Lao Tzu says, *the Nameless is the origin of Heaven and Earth, Therefore let there always be non-being, so we may see their subtlety*,' it was Wei-Li's turn to comment.

'All right, all right, kids, but the work you have to do to get your degrees is not an illusion or non-being,' George responded. After a pause, he added, 'Perhaps we should call it a day. We have covered pretty well most of the black hole basics. Alfie, before I forget, I have made an appointment with our astronomer friend Mike to visit the University Observatory the day after tomorrow. Don't forget. Then maybe next week all of us, you, me, Mike and these three delinquents, will have dinner at Bruno's. We can tie up some loose ends still left in our discussions. How do you like that?'

'Fabulous!' I said.

'Especially if the professor charges the dinner to his grant!' Wei-Li was exuberant.

'Hush, Wei-Li,' George said with finger on lips, 'What if the Dean hears you?'

'Please, please, let me organize the menu if we are having an Italian dinner at Bruno's,' pleaded Sunny.

'Sure, Sunny, talk to Bruno,' assured George and turning to me remarked, 'This girl knows the Italian language and Italian food pretty well.'

'She is reading Dante in the original, at least that is what she claims,' Wei-Li added.

'There are a lot of things in Dante's *Inferno* that sound like black-hole physics,' Sunny said to me.

'Really, I must read *Inferno* again one of these days – in translation though,' I told Sunny, and got up. 'George, I have already taken too much of your time. I know you people have work to do. Thank you all for a wonderful evening. Bye now.'

The four of them joined in wishing me a pleasant evening or what was left of it. Before letting myself out of George's office, I looked back as I had done the previous evening. As I had expected, those four were already warming up for the ensuing discussion. Paul was erasing the old writing on the black board. The other two students were taking out their notebooks from their rucksacks. George was leaning back in his chair totally relaxed. As I stepped out into the corridor, I felt happy for them. They had a beautiful world of their own. And I had mine, didn't I?

Chapter 15

A DATE WITH DANTE

Last night I felt rather restless. I thumbed through books I had already read – poetry of all kinds, detective stories, fantasies, and books of drawings and paintings. It was of no use. So, I decided to write a poem! Let me show it to you. I couldn't decide upon a title though. I have suggested three of them in fact. You may choose the one that you think is most appropriate. Here it is.

THE PLIGHT OF LIGHT
OR
LAMENTATIONS OF LIGHT
OR
LIGHT'S LIBERTY LOST

Oh, my dear Albert E,
Tell me, what have I done to thee?

I wandered fast and I wandered slow,
Much as a meandering river would flow.
But you made me travel with constant c
Whatever the speed of the observer be.
You tucked me firmly into a curved space
I must now climb hills red in the face.
Straight as an arrow I used to go
How painful it is now to bend like a bow.
Oft I get trapped in the gravitational field

Of your astronomer friend Karl Schwarzschild.
Ever since the Big Bang, a long time back,
I have been stretched out on the cosmic rack.
Worst of all, I'm doomed to a double life
As both particle and wave in schizophrenic strife.

Oh, my dear, dear Albert E,
Tell me, why have you done this to me?

Oh, enough of this, I thought, let me take a bath instead. I am afraid that I am getting addicted to taking bubble baths. I cannot help it. Who could? Tell me. To lie in my magical bathtub, eyes closed, submerged in the warm bathwater in a state of indolent insouciance and letting my mind wander freely wherever it wants to go. And then there are the bubbles surrounding me, soothing every muscle and sinew in my body. Fortunately, however, the urge to indulge in this luxury takes possession of me more or less only on those occasions when I have had discussions with George. As I told you on an earlier occasion, I had to economize on the precious mixture, or whatever was left of it, as Al's store was still closed. I added just half a spoonful to the bathwater and got in. The water started effervescing and the bubbles appeared, large and small, single ones and pairs of them. I observed that most of the bubbles had inside of them dark specks that were shaped like squashed spheres and whirled around making the bubbles spin along too. They were creating little swirls in the bathwater, making my body tingle all over and relax completely. I sighed in supreme contentment, closed my eyes and let my mind drift away.

When I opened my eyes, I found myself standing in the foyer of the strangest building one could ever imagine. There were staircases all over the place, installed in all directions at different angles. Some of them even had steps on both sides. There were a number of people in the house, who looked like mannequins in a clothes store, with no facial features at all. They were engaged in a variety of activities. One of them was carrying a tray loaded with food and drink apparently to serve some people sitting at a table, and another was taking a bucket out. So on and so forth. Amazingly enough, these people, if you could call them that, were moving or sitting at all possible inclinations, some even in upside-down positions. It brought to my mind a picture, a lithograph to be exact, that I had seen not too long ago. I could not place it immediately.

'I am sure you will recognize the original design on which this building has been constructed,' said a voice behind me. I turned around not at all surprised. I have become quite accustomed to these unexpected occurrences.

The person, who was standing behind me and who had spoken, had in all probability emerged from one of the many doors, while I was inspecting this extraordinary house. In his twenties, this man was of medium height, almost imperceptibly stooped, and well built with a large head on broad shoulders that seemed to be quite powerful. He had thick black hair, a slightly aquiline but somewhat fleshy nose beneath which he sported a short moustache. His brown eyes could assume different aspects, penetrating or distant and dreamy, or mischievously twinkling, but above all they reflected an innate kindness. He wore a somewhat crumpled, light-coloured three-piece suit with crossed stripes, and sported a loosely knotted tie.

'You will discover that this house is built like M.C. Escher's drawing entitled *Relativity*, which, I am sure, you have seen,' the stranger informed me. 'Each person you see here has his own frame of reference. Who is upright, who is at an angle, who is upside down? It is all relative, Sir. You must have realized that there is no gravity acting on these people. Otherwise they couldn't have been in different orientations like this.' Then as an afterthought he added, 'Dear me, I forgot to introduce myself. You may call me Bert. In an indirect way I may be held responsible for the concept of this house. But that is neither here nor there. Ah, I like that expression, neither here nor there. Seems to suggest the relativity of space or should we say the non-relativity of space!' Bert, as he called himself, bellowed with booming laughter. That extraordinary laughter! Where had I heard it before? I wondered.

'Let me show you around a bit,' Bert offered. 'It is quite interesting, you know, relativity always is.'

Bert led me to one of the closed doors and stopped.

'Before we enter this chamber, let me explain what we are going to see in there,' he said. 'It is popularly known as the Gallery of Gedanken Games. Or simply Three Gees for short. In the old days, many scenarios were created in this room using toy trains and toy people to illustrate some basic principles of relativity. You must have heard of this very inventive chap by the name of George Gamow. He contributed a gedanken scenario too. But, technology has progressed enormously since those times, hasn't it? Well, progress often seems to be a backward journey too, like the retrograde motion of a planet, doesn't it? Anyway, what we are going to witness has hardly any resemblance to the old stuff. Everything has been now upgraded in concept, and in its presentation by the techniques of virtual reality. Virtual reality? How can reality be virtual, *mein Herr*? You have a paradox there. Do you know the variant of paradox? It is orthodox, like *para*- and *ortho*-hydrogen. What do you say?' Bert let out his boisterous laughter.

After a pause, Bert continued. 'Just a word more. As in a movie, we shall be able to see instantaneously what may be happening at another place, at another time. The past, present, and future may get mixed up as well. That way, we may be transcending physical laws. But then, we are allowed such luxuries when we are in the realm of pure thought, are we not? The same goes for dreams and fantasies too.'

Bert opened the door with a swift movement, ushered me in, and quickly closed the door. I could see why. The room was filled with some sort of thin mist and Bert probably did not want any of it to leak out.

'It is not ether, rest assured, for ether does not exist,' Bert declared. 'It is a special kind of gaseous material, something like rubidium vapour. It drastically reduces the speed of light you know, thereby enhancing relativistic effects. Whatever it is, it is quite safe.'

When my eyes became adjusted to the slight haze, I could see quite clearly. We were in what looked like a small old railway station. It was empty except for the stationmaster, who looked exceedingly young. He was pacing up and down impatiently, darting frequent glances at the big wall clock.

'Ah, you noticed how young the stationmaster appears to be. Must be a trainee. Where there is a train, there is a trainee,' Bert exploded with laughter.

'The train is obviously late,' observed Bert wiping away his tears, which had been caused by his mirth and not by the vapours filling the station. 'You know why? The train is running too fast. Ah, please allow me to explain. Some young, overzealous engine driver must be driving the train at great speed hoping to arrive at this station early enough. He thinks he is keeping good time, you know. Because, according to his own observation, his clock is running at the normal rate. But, in order to gather speed, he had to accelerate and his clock ran slow compared to the unmoving clock on the platform. When he wants to come to a stop, he will have to decelerate and again his clock will run slow. What is the end result of all this? The train will arrive late as judged by the impatient stationmaster here, who obviously measures time by the wall clock. Had the engine driver attempted to drive the train faster than at present, the delay would have been even greater because of the higher acceleration and deceleration required. In short, the faster you run, the later you arrive. Another paradox of relativity for you.'

I noticed that the platform on the other side of the railway tracks appeared quite modern, equipped as it was with gleaming, new fixtures including a digital wall clock. 'Ah, that is how the railway station would appear a few decades from now,' said Bert. 'As I explained earlier, we are looking at a scene that belongs to the future, which is not possible in the real world.' At that moment, I noticed a porter on the opposite platform. He was rather old and heavy, but had a striking resemblance to the stationmaster, perhaps an uncle of his, I thought. With some difficulty he was descending the steps leading to the subway passage that connected the two platforms. He disappeared into the passage. Soon enough we heard the hoot of the approaching train at a distance. Presently, it appeared speeding very fast, as Bert had guessed. The compartments appeared acutely foreshortened on account of the Lorentz contraction.

'The compartments should actually appear rotated, rather than compressed, as you may know,' Bert remarked. 'I must speak to the virtual-reality people, who create the gedanken games, and have it corrected.'

Possibly because of the misty haze, the engine's running lights had been switched on, and glowed deep blue.

'Ah, the Doppler shift has made the lights moving towards us appear blue,' commented Bert. 'Have you heard the story about the physicist Michelson? It seems he was once driving his car too fast to stop at a traffic light that had just turned red. A policeman stopped him and hauled him before a magistrate. Michelson explained that on account of the Doppler shift the traffic light had appeared green to him and so he had driven on. Now, the magistrate knew enough physics; for all you know he might have been a frustrated physicist – as many of them are. He observed that Michelson must have been driving nearly at the speed of light, if red were to appear green to him. So he fined Michelson not for ignoring the red traffic light but for speeding. How do you like that?'

While Bert was telling me this story, many events were occurring with confusing rapidity. The train came to a grinding halt and all the Lorentz-contracted compartments regained their normal dimensions. The angry stationmaster was shaking his fist at the engine driver pointing at the wall clock with his other hand. The driver, in his turn, was pointing at his own watch. Evidently the two were reading different times. In the meantime, the old porter had appeared at our end of the subway passage. At close quarters, I could make out his startling resemblance to the stationmaster even better than I had as when he was on the opposite side. When he saw the stationmaster, his face registered extreme surprise and then lit up with joy. He was now rushing towards the stationmaster with his hands outstretched. The latter looked up sharply. At the sight of the old porter approaching him, his face twisted into a grotesque expression of incredulous shock and horror. With a highly distorted exclamation that sounded like, 'Good Lord! It can't be. He is long dead and gone!' he collapsed and lay motionless.

From the crowd that had quickly gathered, a man stepped out and knelt beside the prone figure. Judging from the bag he had placed on the ground, he must have been a medical doctor by profession. He took the pulse of the stationmaster, while looking at his watch. 'Either this man is dead or my watch has stopped,' announced the doctor. I looked at him closely. He wore round, metal-rimmed glasses. His thick eyebrows and moustache looked like a painted-on job. He vaguely reminded me of the oldest of the three brothers who made up a well-known comedy team. 'Hmm, no doubt about it, dead as a duck, if not duck soup,' said the doctor. 'No injuries though. My considered expert opinion is that the man has succumbed to extreme shock. I have nothing more to say and nothing more to do.' He hurried away mumbling about a date he had to keep at the opera that night.

Then the strangest thing happened. The face of the porter contorted in a wild, convoluted, maniacal expression. He started to laugh hysterically, shouting repeatedly, 'I don't exist. I don't exist.' After calming down a little, he explained himself to the baffled onlookers.

'You see, gentlemen, before the train arrived, I was on the opposite platform, an old, fat porter, or a portly porter if you like,' he said. 'Not too long ago, an absent-minded professor dropped his suitcase marked 'Exotic Material' in the subway passage. He never came back to collect it. But I remembered that he was talking to himself something about the possibility of the subway passage becoming a wormhole, whatever that might be. Today, for the first time since then, I crossed over to this side of the railway station through that passage. To my utter astonishment, looking at the old appearance of this platform, I realized that I had emerged into the past. And then came the most uncanny revelation! I see that the stationmaster is none other than my grandfather. That is why I look exactly like him, genetics and all that, you know. I had seen his photograph, taken in his youth and could immediately recognize him. I had not seen him in flesh, since he had died before I was born. Naturally, I rushed towards my dear grandpa with joy, arms outstretched to embrace him. But when he saw me, he must have thought that he was looking at a ghost – his long dead father come back from the grave, poor man. Because, his own father, my great-grandfather, looked exactly like me, you see. But you know what? My grandfather was still unmarried when he died. He passed away, a merry bachelor in fact, long before I was born. Which means that I couldn't have been born. Therefore, it follows clearly that I don't exist.' The old porter paused while this extraordinary fact took a few seconds to sink in and grip him again. Then, he started shouting, 'Oh, ye gods, I don't exist, I don't exist!' Gesticulating wildly, the man looked at the crowd as if seeking their opinion. Some of them seemed to be quite frightened.

Then the onlookers scattered walking backwards. The stationmaster got up, and the old porter also trudged backwards towards the subway passage. The train sped in reverse, its wagons contracting again, and the engine's running lights glowed blood red because of the Doppler shift as the train receded from us and vanished into the haze.

'That was an ontological paradox – the portly porter not existing,' commented Bert. 'The best way to solve a paradox is to make sure that it goes away. That is why the whole sequence was run backwards in time. Wormhole indeed! I am sure you have heard about it. You have to be careful if you crawl through a wormhole though. An early bird might get you.' Bert roared with laughter and added, 'Well, sir, there are other gedanken games played out here. But we must move on.'

Bert led me out quickly and shut the door. We were back in the foyer of the relativity mansion. I happened to look out of one of the windows. Another small building, perhaps an annexe to the main one, caught my attention. I could not make out its outline that seemed to be rather blurred as though it was out of focus. 'Nothing wrong with your eyesight, let me assure you,' said Bert smiling. 'We call it the quantum cottage. Evidently, its features are fuzzy thanks to good old Werner's uncertainty principle.'

Suddenly, there issued forth from the cottage a loud wail of some animal apparently putting up a fight.

'Ah, that is Erwin's cat you know,' Bert informed me. 'That Erwin is a maniac, trying to kill the cat time and again. Poor thing is half dead all the time. Fortunately the SPCA got wise and now Erwin can only feed the cat sleeping pills and make it doze off, stay half-asleep and half-awake I mean.'

The wailing of the cat turned abruptly into a triumphant squeal followed by absolute silence.

'Well, well, what do you know, the cat must have got better of Erwin and fed him the sleeping pills!' exclaimed Bert with glee. 'Now both of them are sound asleep and silently awake. There is a whole bunch of loonies over there. And the looniest of them all is called Niels,' Bert confided conspiratorially in a whisper. As if thinking aloud, he added, 'I suppose I must myself accept some blame for the state of affairs over there in that quantum cottage.' Then turning to me, he said, 'Well, forget what you have seen and heard. The quantum cottage is not part of reality.'

Bert led me to another part of the building where a second gentleman was waiting for us. Dressed in a dark three-piece suit topped by a loosely knotted tie like Bert, he was about ten years older than Bert and a little heavier. His wavy hair, flecked with grey, was getting somewhat unruly while his moustache was on a bushier side than Bert's. It dawned on me, rather forcefully, that this man bore a striking resemblance to Bert, as if, in fact, Bert had grown ten years older. At the same time an eerie feeling took hold of me that I had met a much older version of these two men somewhere long ago. I could not recall where and when. Like a waking dream that you try to remember, the image faded away.

I realized with a tinge of self-consciousness that both Bert and the stranger were watching me with knowing enigmatic smiles. 'Allow me to introduce my friend here,' Bert broke the silence. 'This is Mr. Stone. He will escort you from here onwards. It was a pleasure taking you around, *mein lieber Herr*, and surely we shall meet again.'

Bert disappeared, presumably returning to the foyer of the building. Mr. Stone looked at me his eyes twinkling. 'You may call me just plain Stone, no need for the Mr or any other title for that matter. We are all informal here, you know,' he said as he opened the door in front of us. 'Welcome to the Wonder Way to the Warped Worlds, or Four Ws for short, like the Three Gees you just visited! But, watch your step, it could be quite tricky walking around here.'

The hallway we entered reminded me of another one of Escher's lithographs, namely the *Print Gallery*. The whole place was curved, the walls, the pillars, the floor and everything else. Even the pictures that hung on the walls, which included Escher's depiction of twisted surfaces like the Möbius strip, were curved too.

'Yes, sir, we are indeed in a world of warps,' said Mr. Stone. 'I don't mean just the two-dimensional surfaces like the walls. That is nothing. But the very spacetime we are in is itself highly curved. Obviously, you cannot see it or feel it. Believe me, the spacetime here is warped in intricate ways. One advantage of this is that we can travel in time with utmost ease. You know, Sir, one can also travel in time through one's imagination. I am sure you must have done that often enough. I am told that one can achieve this by spiritual means too. I don't know about that. Here, just by moving around you can travel not only in space but in time too. It is easy to imagine travelling in space wherever you want, but how do you visualise moving around in time? Time flows like a river, *ja*? What if the river bends along a winding course, a meandering river that is? Then just a hop would take you from the present to the past or to the future.'

Mr. Stone paused before continuing as if to give me some time to digest what he had told me.

'Just one more detail before we proceed further. Suppose you travel back in time and come across real people of that age. Then obviously you would find them talking about their experiences confined to their own times. On the other hand, suppose we invoke fictional characters of the past and bring them to the present. Wouldn't it be possible that they might discuss, among other things, the modern day findings, which their original creators might not have even dreamt of? Wouldn't it be strange and intriguing? Well, this is what we are going to encounter now. Don't be surprised if the people you are going to meet talk about your favourite topics in their own quaint ways. All right, enough of my own harangue – with age one grows talkative – let us go.'

Mr. Stone conducted me with utmost caution along the hallway, which eventually led to, how do I put it, nothing, absolute nothing. Can you imagine pure space with no objects in it, not even a speck of dust, no points of reference at all? That is what it was, space in its elemental form, incredibly beautiful, but - let me admit it – a little frightening as well. After spending the briefest moment in this vast emptiness, we found ourselves in the most unusual place I have ever visited.

It was a large room, crammed with a variety of artefacts in addition to the usual furniture, such as a dining table, a writing desk, and a bookshelf. One of the corners was occupied by a table with an acid-stained deal top that held bottles of different coloured chemicals, beakers, and other aids for carrying out experiments, and a low-powered microscope. Above the table on the wall hung a stick rack as well as a shield and a pair of swords, apparently trophies from some war or the other in the East. Littered everywhere were stacks of paper tied up carelessly with string. At the centre of one of the other walls was a wooden mantelpiece transfixed to which by a jackknife was a bunch of letters, while next to it hung a Persian slipper with tobacco spilling out of it. Two comfortable chairs had been arranged facing each other on either side of the fireplace.

Someone, whose face I could not see, concealed as it was behind the newspaper he was holding up, occupied one of these two chairs. He was sitting motionless as he read the paper with great concentration. Facing him, sat a man of extraordinary aspect. His very person and appearance were such as to strike the attention of the most casual observer. In height he was rather over six feet and so excessively lean that he seemed to be considerably taller. His eyes were sharp and piercing, while his thin, hawk-like nose gave his whole expression an air of alertness and decision. His chin, too, had the prominence and squareness, which mark the man of determination. He stood up, walked over to the mantelpiece and filled the pipe he was holding in one of his hands with tobacco from the Persian slipper, and returned to his chair. After lighting the pipe, he regarded his companion for a while, eyes half closed, before speaking.

'It must be a most interesting article on astronomy you are reading, Watson,' said he.

His companion lowered the newspaper in astonishment, 'Really, Holmes! How did you arrive at such an accurate conclusion, may I ask?'

Of course it was Dr. Watson, somewhat stocky in his build with soft features, in complete contrast to Sherlock Holmes, seated opposite to him.

'You know my methods, Watson. It is founded on the observation of trifles,' answered Holmes. 'In the present case, I noticed that first you glanced at the newspaper in a cursory fashion holding it wide open. Then, having found something of interest, you folded the paper and buried yourself in it. I surmised that whatever you were reading was quite absorbing from the fact that although the fingers of your left hand trembled and twitched from time to time, obviously due to the pain emanating from your shoulder that was shattered by a bullet in the Afghan campaign, you did not put away the newspaper. Besides, I can see the number of the page facing me from which I can easily tell the page number on your side. Today being Tuesday, I know that the page you are reading is devoted solely to matters of science. Nowadays, the only exciting developments in science are confined to astronomy, in which you are deeply interested. Therefore, I came to the conclusion that you must be reading a very interesting article on astronomy. Quite elementary, my dear Watson!'

'Amazing!' exclaimed Watson. 'You must read this article, Holmes. It describes the evolution of stars like our Sun and heavier ones.'

'My dear fellow, pray enlighten me as to why stars should be of any consequence to me, since they are not in the least connected with crime or its detection.'

This remark of Sherlock Holmes was perfectly in keeping with what Watson had recorded in *A Study in Scarlet* regarding Holmes' attitude towards the Solar System. Let me quote the relevant passage for you.

> *His ignorance was as remarkable as his knowledge…My surprise reached a climax, however, when I found incidentally that he was ignorant of the Copernican Theory and of the composition of the Solar System. That any civilized human being in this nineteenth century should not be aware that the earth travelled round the sun appeared to me such an extraordinary fact that I could hardly realize it.*
>
> *'You appear to be astonished,' he said, smiling at my expression of surprise. 'Now that I do know it I shall do my best to forget it.'*

'But, Holmes, this article is really interesting,' remonstrated Watson. 'It explains the life and death of stars.'

'Death, did I hear you correctly, Watson?' Holmes sat up with interest. 'Death, like crime, always fascinates me. Tell me then what this confounded article of yours has to tell us about death.'

'It says here that, when stars die, they become invisible.'

'Alas, Watson, frail is human nature and short is human memory,' remarked Holmes. 'Yes, when stars, I mean celebrities, die they become invisible. Why, even during their lifetime, some fade away.'

'When a star like the Sun burns up all its fuel, it turns into an invisible black dwarf,' Watson continued his exposition.

'A black dwarf indeed,' frowned Holmes. 'We encountered a hideous dwarf in our adventure which you chronicled under the title *The Sign of the Four*, did we not? He was from the Andaman Islands in the Bay of Bengal. He was quite dark, almost black, but hardly invisible, in my considered opinion.'

'Then stars heavier than the sun are expected to become neutron stars.'

'Neuter stars you mean,' corrected Holmes. 'The famous or infamous *Castrati*, who used to sing in Italian operas! Yes, they had a tendency to put on weight and become quite heavy.'

'Then, there are even heavier stars. When they die, they become black holes.'

'Well, wasn't there one in Calcutta, Watson? You must have come across it when you were in India.'

'Oh, yes, there was some talk about the Black Hole of Calcutta, when I was in Bombay on my way to Afghanistan,' concurred Watson. 'But we are talking about black holes in the celestial realm, Holmes. The article claims that when a very heavy star collapses, it becomes a black hole. And nothing can come out of it, no matter, no information, nothing.'

'This is most curious, Watson,' commented Holmes evincing keen interest. 'No information at all, eh? There may be a connection to crime here after all. But, tell me first if you will, how these peculiar astronomer fellows have found out so much about dead, invisible stars.'

'By building detailed theories about the evolution of stars as I understand it,' answered Watson.

'But you know my dictum, Watson: *It is a capital mistake to theorise before one has data. Insensibly one begins to twist facts to suit theories, instead of theories to suit facts.*'

'Holmes, it seems there is plenty of circumstantial evidence for the existence of these objects,' pointed out Watson.

'Then again have I not told you before? *Circumstantial evidence is a very tricky thing. It may seem to point very straight to one thing, but if you shift your own point of view a little, you may find it pointing in an equally uncompromising manner to something entirely different.*'

'Still, astronomy could be an exception, you know.'

'An exception, Watson? *I never make exceptions. An exception disproves the rule.* Be that as it may, pray tell me, how do they pin down your elusive black hole amongst the three different kinds of invisible entities?'

'Well, by a process of elimination, Holmes,' explained Watson. 'If an invisible object is neither a black dwarf nor a neutron star, it must be a black hole.'

'Capital, old chap! *It is an old maxim of mine that when you have excluded the impossible, whatever remains, however improbable, must be the truth.* What happens to all the mass that went into this insane black hole of yours?'

'It collapses to a point, which is known as a singularity, Holmes. On the other hand, it has also been conjectured that something called quantum effects might arrest the collapse, thereby averting the formation of the singularity.'

'*Arrest* I like that word! But a conjecture you say? *Ah, my dear Watson, there we come into those realms of conjecture, where the most logical mind may be at fault.* I have said it before and I shall say it again. *Singularity is almost invariably a clue. The more featureless and commonplace a crime is, the more difficult it is to bring it home.*'

'But, Holmes, how is the singularity or the black hole connected to crime?'

'Is it not obvious, Watson?' asked Holmes rubbing his hands in relish. 'Nothing that enters your infernal black hole can come out you said, no matter, no information, no whatsoever. What if a murderer were to throw both the murder weapon and the body into a black hole? *Corpus Delicti*! Not even a whisper of evidence can issue forth. Diabolic, Watson!'

As Holmes paused to ponder his own idea, a dark frown appeared on his countenance.

'My God, Watson, what if Moriarty has learnt about this atrocious black hole? *He is the Napoleon of Crime, Watson*.'

'And the criminal among the Napoleons. I mean *The Six Napoleons*, Holmes.'

'You have the strangest manner of expressing your thoughts, my man,' commented Holmes. 'Coming back to Moriarty, his achievements in the fields of mathematics and science are brilliant, Watson. Take for instance the binomial expansion, which was known to the Hindus and Arabs, and was further developed by the likes of Isaac Newton. What remained for Moriarty to do, many have wondered. Well, I believe that he has applied this expansion to fields other than algebra like human consciousness. But this was child's play for a man who wrote his treatise *On the Dynamics of Asteroids*. Who knows, Watson, the title of this treatise might have later on inspired someone named Albert Einstein to call his paper *On the Electrodynamics of Moving Bodies.* Then again, there is little doubt that Moriarty anticipated this Einstein fellow's discovery of the mass-energy equivalence. My own work on the element Uranium was related to this, Watson. But I did not pursue the matter further as I foresaw the destructive potential of my discovery. It is rumoured that Moriarty is entertaining astonishing ideas on the possibilities of space travel. In short, my dear fellow, I would not be surprised at all if Moriarty is thinking right at this moment of making use of these ominous black holes of yours for criminal purposes. Enough said, Watson, it is all idle talk. I cannot allow my mind to stagnate. I need a case to solve, a problem to stimulate my faculties, in the absence of which I am left with but only one alternative.'

Taking long strides to the mantelpiece, Sherlock Holmes took a bottle containing his infamous seven percent solution of cocaine and his hypodermic syringe from its morocco case, as Watson watched in helpless horror. At that moment, in came Mrs. Hudson, the housekeeper, after a perfunctory knock on the door. She placed on the table a brass salver with an envelope on it saying that it had been slipped in underneath the front door. After surveying the room with obvious disapproval, she withdrew shaking her head.

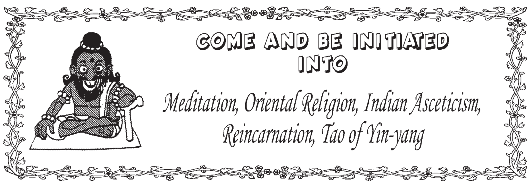
'Aha, Watson, what do we have here!' exclaimed Holmes picking up the unopened envelope. He looked at it closely, felt it with his fingertips, sniffed it all over, and then tossed it over to Watson saying, 'Tell me what you make of it, Watson.'

Watson examined the still unopened envelope carefully and answered, 'Not much I am afraid, Holmes. It is a very ordinary envelope made of some kind of ornamental paper and somewhat soiled at places.'

'On the contrary, old chap, it tells us quite a bit,' Holmes chuckled. 'It has been sent to me by a careless, sloppy Indian cook with unhygienic habits, who can speak French, and who has recently arrived from his native country. He has injured his finger probably while cutting vegetables and has attempted to fake his handwriting.'

'This is incredible, Holmes,' exclaimed Watson in sheer amazement. 'How could you deduce so much from the mere examination of this envelope?'

'First of all, the envelope has been made from a special kind of paper and the ornamentation you referred to is produced by a process called marbling. Such paper is made by a small community in the French colony of Pondicherry in India. They would not sell their products to anyone who did not speak their language. National pride, my dear Watson! The material is still fresh and therefore our man must have arrived from India recently. The envelope is soiled at places because of boiling curry sauce that has splashed onto it. This unequivocally indicates that the person in question is an Indian cook, sloppy and careless in his manner. In addition to sight and sound, olfactory response can reveal a wealth of information, Watson, provided you have a well-tuned nose of decent proportions like mine. I can detect not only the odour of the thin Indian cigar open at both ends known as the *lunkah*, which the man has smoked while cooking – a very unhygienic habit indeed, but also the strong smell of tincture of iodine, which he must have applied to his injured finger, a result of careless cutting of vegetables. Now, he has tried to disguise his handwriting by slanting the letters towards the left, but two of the letters have been slanted towards the right inadvertently. It is all quite simple. Let us see what is inside the envelope.'



Sherlock Holmes easily pried open the envelope with his long fingers. Sniffing at it once again, he commented dryly, 'Just as I thought! Sealed with rice gruel as can be expected of a cook. Aha, what do we have here!'

Holmes extracted from within the envelope what seemed to be an announcement of some forthcoming event. It depicted a man with flowing hair and a full beard, wearing strings of beads. He appeared to be quite dark in colour. Next to this picture was written the announcement in large letters. Beneath were given the details regarding the venue, the date and time of this strange event.

'This is a challenge, Watson,' said Holmes jubilantly. 'What do you make of the person pictured here?'

'A holy man I suppose,' answered Watson.

'How about his colour?'

'Quite dark, in fact black I would say.'

'A black holy man or, shall we say, a *black holey* man. A man associated with black holes, Watson!' laughed Holmes. 'And look at the first letters of the string of esoteric, religious practices listed.'

Watson pondered for a moment and exclaimed in disbelief, 'My God, they spell MORIARTY, Holmes!'

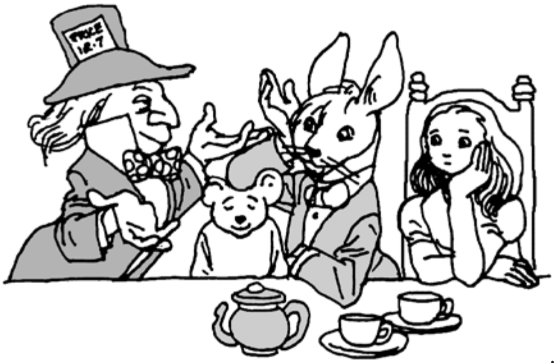
'Devilry, my dear Watson! This promises to be a three pipe problem,' ejaculated Holmes. 'And the event is scheduled to take place within an hour. There is not a moment to waste.'

Sherlock Holmes took out a revolver from the desk drawer and slipped it into his jacket pocket. Donning his deerstalker hat and putting on his long caped overcoat, he called out to his friend, '*Come, Watson, come. The game is afoot. Not a word! Into your clothes and come.*'

Holmes dashed out of the door, while Watson hastily picked up his hat and coat from the rack and followed him. Immediately the sitting room too disappeared, leaving Mr. Stone and me in the vast empty space again.

'An interesting pair, I hope they pinned down the black holey man, whoever it was,' Mr. Stone laughed. 'Now let us visit some more familiar figures.'

The scene changed as Mr. Stone spoke. There was a table set in the open. I was startled to see Fernando and his friend Marchado Harera having tea. They were still dressed in the same peculiar manner as I had seen them last, Fernando wearing his top hat with the price tag intact. Almost drowning in a large armchair at one end of the table was little Falicia in her white frock. Far away in the background I could see a figure dressed in deep red, presumably it was Maria, once again wearing the same dress as I had seen her in recently. The entire menagerie of Falicia seemed to have been let loose. For instance, what looked like her furry tailed cross between a mouse and a squirrel was sitting fast asleep between the two men. Strangely enough, it had grown so large that the two men were using it as a cushion, resting their elbows on it while talking over its head. All the other animals had grown big too, like Blanco the white rabbit, which kept flitting in and out. Macho the turtle was sitting dolefully on a big rock far away, and Falicia's cat had perched on the branch of a tree. I soon realized that this was not Fernando's household at all, but characters from Lewis Carroll's *Alice in Wonderland.* Those gathered at the table were the Mad Hatter, the March Hare with the drowsy Dormouse in between, and of course Alice herself.



'Have some wine,' the March Hare invited Alice.

Alice looked all around the table, but found no wine at all.

'I don't see any wine,' she commented.

'There isn't any,' admitted the March Hare. 'It was lost in the free-for-all.'

'He means the free fall,' interjected the Hatter.

'Does a flea fall or a fall flee?' mumbled the Dormouse in its sleep. The Hatter and the March Hare, sitting on either side of it, tried to wake it up by pouring hot tea on its nose but to no avail.

'Could you tell me what day of the month it is?' the Hatter asked Alice, looking at the watch he had taken out of his vest pocket.

Alice thought for a moment and answered, 'It is the fourth of May I think.'

Frowning, the Hatter shook his watch and held it to his ear. 'My watch is off by two days then,' he announced with annoyance.

'You shouldn't worry about that,' Alice reassured him. 'Each one measures one's own time. It is called the proper time I believe.'

'What you believe is quite immaterial, you know,' commented the March Hare. 'Moreover, if time is not the same for everyone, then it should be called the *improper time* and not *proper time*, since it's behaviour is highly improper.'

Alice looked at the Hatter's watch and exclaimed, 'Why, this watch shows only the day of the month but not the hour and minute not to speak of the second.'

'That is because time runs so slow around here,' explained the Hatter. And then he added in a loud whisper, 'they say there is a Hole down under, very black in colour, where time stands still.'

'Yes, yes, time stands still on one foot, actually on just one toe like a ballerina,' confirmed the March Hare.

'If time stands still and does not flow, how can you tell time?' asked Alice.

‘Tell time what?’ questioned the Hatter.

‘Never tell time secrets. He is a big blabbermouth,’ warned the March Hare.

‘How can time have a mouth?’ Alice was puzzled.

‘If time can have a foot to stand on, why can’t he have a mouth to blabber with?’ asked the March Hare.

At that moment, what looked like Falicia’s Blanco, the white rabbit, ran in muttering to itself, obviously very worried, ‘Oh dear! Oh, dear! I am too late!’ Then it took out a watch from its waistcoat pocket, looked at it, shook its head and hurried on.

‘That rabbit is always late because he runs too fast,’ said the Hatter. ‘The faster you go, the later you arrive. That is why he lost the race to the tortoise. It is all due to something called time dilation, I am told. Time is not only able to stand on his toe, but he can also be stretched out. He is a trained contortionist. He ought to be in the circus you know.’

‘Not only that, that rabbit keeps going near that Hole down under and coming back. That makes him late too,’ added the March Hare.

‘I don’t understand any of this,’ cried out Alice in despair.

‘If you don’t understand, then sit over,’ mumbled the Dormouse in its sleep, whereat the other two poured more hot tea on its nose.

‘Of course you wouldn’t understand,’ the Hatter told Alice sternly. ‘Only three people in the whole world understand it – me, the March Hare, and the Dormouse, who sleeps on the matter all the time.’

‘I wish he would sleep on a mattress, that would be more comfortable,’ commented the March Hare dryly.

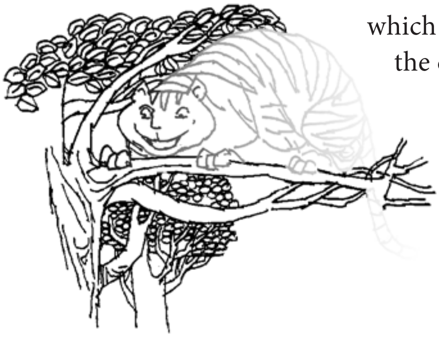
‘I understand it all as well as you do,’ said a purring voice. It was the cat sitting high up on the tree branch, grinning from ear to ear showing all its teeth. ‘I keep going near the Hole down under and keep coming back all the time too. It is great fun.’

‘Oh, that Cheshire Cat boasts too much,’ said the Hatter. ‘It is true that he keeps going near the Hole. That is because he has nine lives. He can take the risk of losing one of them getting near the Hole.’

‘But it does not have nine tails unlike the cat-o’-nine-tails though,’ observed the March Hare. ‘If it were ever to fall into the Hole it would be cat-astrophic.’

‘I agree cat-egorically,’ said the Hatter.

‘Watch me – yes, it has all to do with the watch and time, yours and mine – just observe!’ said the cat, its grin widening even more. Then the Cheshire cat vanished slowly, beginning with the tip of its tail and ending with the grin,



which lingered on for a long time after the rest of the cat had gone.

Meanwhile, I could see the lady dressed in red, whom I had taken to be Maria, approaching Alice. It was in reality the Red Queen from *Through the Looking Glass.* As soon as she reached Alice, the Red Queen took hold of Alice's hand and started running. The Red Queen ran so fast that Alice had to put in all the effort she could to keep up with her. Still, the Queen went on crying, 'Faster, faster,' making Alice completely out of breath.

The most astonishing part of this whole operation was neither of the two seemed to move, however fast they ran. Just as Alice was getting totally exhausted and could run no more, the Queen stopped.

Alice looked round her in utter disbelief and cried out, 'My goodness, we've been under the same tree all the time! Nothing has changed at all.'

'Of course everything is the same,' the Red Queen answered. 'What did you expect?'

'Well, where I come from you would get somewhere else if you ran the way we did,' said Alice.

'It must be a slow sort of place,' remarked the Queen. 'Now, here, on the other hand, it takes all the running you can do, to keep in the same place.'

'Why is that?' asked Alice.

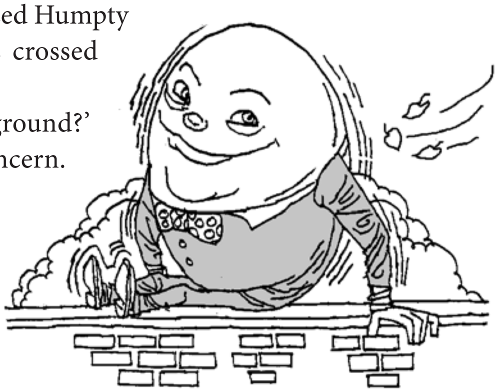
'They say it is because the space around you is turning,' answered the Queen. 'You see, if you didn't run, the space might take you where you didn't want to go. So you must run to stay where you are, my dear.' Then she added in a whisper, 'Don't believe a word of this space itself turning, my dear.'

'Then how do you go anywhere at all here?' Alice asked again.

'Well, if you want to get somewhere else, you must run at least twice as fast as we did,' answered the Red Queen. 'Let me show you.'

How it happened, Alice never knew. Whether she vanished into the thin air, or whether she ran quickly away, there was no way of guessing, but the Red Queen was gone.

The tree beneath which Alice and the Red Queen had been running stood next to a garden wall. Perched precariously on the wall was what looked like a gigantic egg. But on closer examination, one could see that it had eyes and a nose and a mouth. I recognized Humpty Dumpty who sat on the wall, his legs crossed like a tailor.



'Don't you think you'd be safer on the ground?' Alice asked Humpty Dumpty with concern. 'That wall is so very narrow.'

'I don't think so,' replied Humpty Dumpty raising one eyebrow in apparent disdain. 'I am in perfect equilibrium, if you must know. But that is not enough. One must be in stable equilibrium to keep one's balance.' Humpty Dumpty swayed dangerously as a gust of wind blew in and then he came back to his original position. 'Ah, that was a perturbation. But I am imperturbable, because I have an even temper you see. It is only people with odd tempers that fall down from walls. It is called gravitational collapse. But when you fall, you feel no gravity, only levity. That is why falling people tend to laugh. But you must watch out for tidal forces, you can't get rid of them you know. I know you don't know. So let me make you feel some tidal forces.'

Humpty Dumpty first brought his hands together and then moved them apart vertically. At once, Alice started getting stretched out.

'Now I'm opening out like the largest telescope that ever was! Goodbye feet!' cried out Alice. For, when she looked down at her feet, they seemed to be almost out of sight, they were getting so far off. Humpty Dumpty brought his hands together again and Alice regained her normal size. All this made her quite dizzy.

Humpty Dumpty looked down his nose at Alice with amusement and went on.

'If I ever *did* fall off – there is no chance of it mind you – but if I *did*, why, the King has promised to send all his horses and all his men. I don't know what the horses are for, but the men will put me together again. I am told that it is impossible thermodynamically, but the King has assured me that it will be done thermostatically. Anyway, if I fall it will be a great fall. You know why? Because, I am great. I am telling you this in all modesty since I am not an egg-oist!'

'And how exactly like an egg he is!' Alice said aloud.

'It is *very* provoking,' Humpty Dumpty frowned. 'To be called an egg – *very*! I have the shape of an egg, that's true. Do you know why an egg is shaped the way it is? Because of the earth's rotation, that's why. It is called a Machian effect.'

'But in school we were taught that the Earth bulges at the equator and is squashed at the poles because of its rotation,' Alice pointed out. 'But the egg is shaped the other way round.'

Humpty Dumpty pondered this for a while and then declared solemnly, 'Then it is an Anti-Machian effect. You know nothing about tidal forces, nothing about the Machian effects, nor the Anti-Machian effects.' He shook his head in disapproval. 'You have a lot to learn, child. The best person to teach you the Machian effects is, why, the Mach Turtle himself! You go that way and you will find him.'

Humpty Dumpty pointed his finger in the direction Alice was supposed to take. He then shut his eyes and fell silent, taking no further notice of her.

Alice followed Humpty Dumpty's direction. I thought I could see Falicia's turtle Macho, once again grown quite big. No, it was the Mock Turtle or the Mach Turtle, as they called it, sad and lonely, perched on a rock. Next to it, lay basking in the sun a Gryphon with the head and wings of an eagle and the body of a lion. The Mach Turtle sighed and sobbed alternately.

'Humpty Dumpty must have sent you to me,' said the Mach Turtle in a hollow tone looking at Alice through his tears.

'Oh, yes, the Old Egg does it always,' yawned the Gryphon. 'And the turtle here invariably tells everyone about his school days.'

'I do, I do,' sniffed the Mach Turtle. 'For, you see, I had a very happy childhood.'

The Gryphon made an exclamation that sounded like 'Hjckrrh!'

'When we were little, all of us Mach Turtles went to a school in the sea,' the Mach Turtle began. 'Once it used to be a school of fish. But then the fish turned turtle and it became a Turtle School. It was run by a vague, indefinable principal called Mach's Principal. I shall tell you about him later on.'

'Tell her about your school curriculum,' prompted the Gryphon.

'We had the best of education,' sighed the Turtle. 'We had to learn plenty of geometry. To begin with we studied Yulekidean geometry.'

'Why was it called that?' asked the Gryphon yawning again.

'Because a porpoise named Yulekid invented it. He was born on the Christmas Day, which made him brilliant. He gave four hundred and sixty-seven Porpoisitions starting from just ten Preposturates.'

'Hjckrrh, you must explain why they were called that,' said the Gryphon whipping his tail about.

'Because they were quite preposterous. We had to study non-Yulekiddian geometry too. It was very difficult, but it was unparalleled. Too much geometry, awfully difficult!' the Mach Turtle sobbed profusely.

'That is nothing,' scoffed the Gryphon. 'We had to climb up a lofty mountain to study Higher Mythamatics, which included Centaur Analysis.'

'But the best education we got was from Mach's Principal,' the Mach Turtle sniffed on. 'He was very comforting to boot, although he didn't own any. If we were lazy, he did not mind it at all. According to Mach's Principal, our inertia was due to all the other bodies around us. And unlike us, they were busybodies. The Principal was concerned about twisting and turning. He said that if you did a good turn, others would follow you too. He taught us all about turning – turning tides, turning tables, turning turtle, and so on. We had to sing and do a dance called the Bolster-Quadrille.'

'I thought it was called the Lobster Quadrille,' commented Alice.

'No, no, it was called the Bolster Quadrille,' wept the Mach Turtle as tears rolled down its cheek.

'Why was it called that?' The Gryphon repeated its usual question.

'Because we had to do a song and dance number in order to bolster up Mach's Principal, who was quite weak as well as indefinable.'

'Go, on, go on, we don't have all day to listen to you,' grumbled the Gryphon impatiently, which was unfair, considering that it was the Gryphon who had interrupted the turtle in the first place and was asking too many questions.

'We had to go round and round in circles, when we danced,' explained the Turtle. 'As we turned round, so did our partners, and all other creatures of the sea. This was called the Machian Effect. As we went in a loop, we came back to the same point in space. We could also go in a time-loop, keep growing older and then come back to our present, or even to the past, and be quite young again. It was all wonderful, but often quite disconcerting.' The Mach Turtle sighed long and deep many times.

'Why don't you sing the song the *Time-like Loop* for this poor, ignorant child?' suggested the Gryphon.

'Please do, please do,' urged Alice.

The Mach Turtle cleared its throat, sighed, and sang in a voice choked with sobs. This song, *Time-like Loop*, reminded me of Mock Turtle's song *Turtle Soup* I had read in *Alice in Wonderland*.

Beautiful Loop, so round and nice,
In a warped spacetime, there it lies!
Who wouldn't want to round it troop?
Loop for time-travelling, beautiful Loop!
Loop for time-travelling, beautiful Loop!

Beau-ootiful Loo-oop!
Beau-ootiful Loo-oop!
Loo-oop for time-tra-a-avelling,
Beautiful, beautiful Loop!

Beautiful Loop! You've found a way at last
To journey around to your own past.
Go back in time and live it up once more,
Make all your mistakes as you did before!
Beau-ootiful Loo-oop!
Beau-ootiful Loo-oop!
Loo-oop for time-tra-a-avelling,
Beautiful, beauti-FUL LOOP!

The vision of the three characters – Alice, the Mach Turtle, and the Gryphon – dissolved slowly until it finally melted away, as at the same time the melancholy voice of the turtle gradually faded into silence.

'Some say it is all nonsense,' remarked Mr. Stone. 'But what is sense and what is nonsense? It is all relative, don't you agree?'

The space around us seemed to have acquired an ominous character, which I cannot describe adequately. I felt a strong force pulling me. When I looked in the direction of that force, I could see a dark, motionless figure, transfixed in space. I looked at Mr. Stone questioningly.

'This is where I take leave of you, *mein lieber Herr*,' said Mr. Stone, smiling and gesturing towards the mysterious, far-off figure. 'You have a new guide, one who has been to a place from which there is no return, like the one you are interested in. He will conduct you to your final destination. And, of course, rest assured that we shall meet again. *Auf Wiedersehen!*'

With that remark, Mr. Stone disappeared too.

I was irresistibly drawn towards the immobile apparition, a dark sculpture silhouetted against rising luminous vapours. A shock of recognition dawned upon me as I approached him. His features were unmistakable, the long face with the pronounced, hooked nose, and the stern expression. Unmistakable too was his Florentine costume in black – his *lucco*, the straight gown and *capocchio*, the hood. There was no doubt about his identity, it was Dante Alighieri, the great Italian poet, author of the *Divine Comedy.* Indeed he had traversed the *Inferno*, the place one never returned from, guided by another great poet Virgil. Yet, returned he had, for after all it was only the vision of *Inferno* he had entered into and experienced. Now he would guide me through another place in space and time, which one could enter but never return from.

Dante looked straight ahead, gazing into the distance, oblivious of my presence, as I followed him. Then, he recited the opening lines of his immortal poem.

I woke to find myself in a dark wood,
Where the right road was wholly lost and gone.

The words, intoned in a rich, resonant voice, reverberated, shattering the eternal silence of the vast space that surrounded us. Dante was now poised on the brink of his long journey into the night.

So, while my soul yet fled, did I contrive
To turn and gaze on the dread pass once more
Whence no man yet came ever out alive.

That dread gripped me as well. We moved on and I contemplated our entry into the region from which nothing ever came out. Dante stopped and gazed ahead. And I saw the inscription on the entrance etched in phantom letters of fire that blazed and evaporated intermittently.

THROUGH ME THE ROAD TO THE CITY OF DESOLATION,
THROUGH ME THE ROAD TO SORROWS DIUTURNAL,
THROUGH ME THE ROAD TO LOST CREATION.

NOTHING ERE I WAS MADE WAS MADE TO BE
SAVE THINGS ETERNE, AND I ETERNE ABIDE;
LAY DOWN ALL HOPE, YOU THAT GO IN BY ME.

A shiver ran down my spine as I read that inscription. While we went forth and entered the region of churning forces, Dante recounted his own experience, when his companion poet had escorted him among spirits that swirled and writhed in agony, as if irresistible forces churned them up. To me those spirits of the dead represented matter inexorably spiralling in.

Made tumult through the timeless night, that hither
And thither drives in dizzying circles sped,
As whirlwind whips the spinning sands together.

No, nothing could rest here. One had to move perpetually with no hope of ever stopping, with no hope of respite.

Hither and thither, and up and down, outworn,
Hopeless of rest – rest, did I say?
Of the least minishing of their pangs forlorn.

All this was a prelude to the descent down to the infernal regions.

Deep, dense, and by no fainter glimmer lit
It lay, and though I strained my sight to find
Bottom, not one thing could I see in it.
And reach a place where nothing shines at all!

As I followed the poet, who went first, we were engulfed by titanic streams of vapour and gas, rushing along circles in both directions, co-rotating and counter-rotating.

A place made dumb of every glimmer of light,
Which bellows like tempestuous ocean birling
In the batter of a two-way wind's buffet and fight.
As waves against the encountering waves advance
Above Charybdis, clashing with toppling crest,
So must the folk here dance and counter-dance.

As we plunged towards the centre of irresistible attraction, gases poured down all around in rushing intertwined streams. But Dante went on with his poetic exposition. I could feel his excitement as we approached our final destination.

Had I but rhymes rugged and harsh and hoarse,
Fit for the hideous hole on which the weight
Of all those rocks grind and downward course by course,
I might press out my matter's juice complete;
As 'tis, I tremble lest the telling mar
The tale…

Dante's voice trailed off into momentary silence. But then he thundered as if issuing a command.

Vexilla Regis prodeunt inferni!
The Banners of the King of Hell go forth!

At that, as if the floodgates of heaven and hell had been suddenly opened up, matter churning in torrential turbulence gushed down with a deafening roar, sweeping me along. The thought that flashed across my mind was that this was the end, that I would be crushed out of existence. Or would I escape such a fate after all? Was there still some hope? As the dark figure of Dante drifted away, I heard his last comforting words, recalling what Virgil, his guide, had said to him long, long ago.

And he made answer: "Follow but thy star;
Thou canst not fail to win the glorious heaven,
If in glad life my judgement did not err."

Then everything went blank, consumed by absolute blackness.

When I opened my eyes, I found myself drenched in cold sweat, but safe in my bathtub – to my great relief. The bathwater was furiously eddying down my body and swirling away into the drain. I must have dislodged the plug with my toe during my bizarre, hallucinatory trip. As the water ran out, I got up, dried myself and went to bed. Soon I fell into a deep dreamless sleep.

Chapter 16

IMPRINTS OF THE INVISIBLE

'I just love this stretch of road,' said George as we drove to the University Observatory. We were winding our way up a hill, tall trees lined up on either side of the road. Every now and then, the late afternoon sun shone through the green canopy woven overhead by the lush foliage. Beyond the trees grew wild shrubs and grass that covered the slopes. The city below receded gradually, the buildings turning into little boxes and the streets into a web of criss-crossing lines.

Suddenly, without any prior indication, the observatory came into view as we reached the top of the hill. A tall, gleaming white cylinder of a building capped with a metallic dome that resembled the helmet of an ancient Roman warrior. A lone sentinel that surveyed the Earth below and looked up to the stars above.

George rang the bell and the curved door fitting snugly into the cylindrical building opened quietly. Hand outstretched to greet us, Mike stood there with his warm, boyish smile.

'It is wonderful to see you both up here,' said Mike as he ushered us in. 'Since this is the first time you are visiting us, Alfie, let me show you around quickly.' I could see that the interior of the building had been very well planned, making efficient use of every inch of the available space.

'Here is a workshop for minor repairs, Alfie. We fabricate simple gadgets of our own, needed for our observations,' explained Mike as he gave us a guided tour of the place. 'We have two small but adequate rooms for the observers to rest. To sleep and perchance to dream! Occasionally we do have nightmares. From time to time, Nature gets malicious and covers the sky with clouds. We are terribly afraid that we may miss out on the golden opportunity to witness some rare event or the other, you know. Ah, this is the most important spot, the little kitchen that helps keep our body, mind, and soul together.'

After this short trip around the outer periphery of the building, Mike opened the door to the cavernous central observing room and announced dramatically, 'Behold the Queen of the Firmament in all her glory!'

I had seen pictures of any number of telescopes, ranging from the legendary little glazed optical tube of Galileo to the giant at Palomar. But this was different, this one was for real. It looked immense, sturdy struts running from one end to the other forming the framework. There was no tube, which used to be an integral part of the telescopes in the old days. Here was this magnificent instrument that captured the photons, weary messengers that had journeyed for millions and billions of years, and revealed the cosmos to the human eye. I stood riveted gazing at that bridge between the earth and the heavens.

Mike, who must have been watching me, came over and said softly, 'I know the feeling very well, Alfie. Even after all these years here, I too feel it every time I enter this chamber, the overpowering sense of awe.'

We entered the observing room and I found that the telescope was even more impressive from close quarters.

'Let me show you quickly some of the important parts of the instrument,' Mike said. 'Here is the heart of the telescope, the concave mirror ground to perfection. You know they use little concave mirrors in compacts carried by women? That way the lady carrying the compact can see her own somewhat magnified reflection. Let some beauty queen look at her own face in this mirror. It would be a shocking experience. Our mirror would show up every microscopic blemish on the skin.'

'Mike, last time I was here, you had some problem with the telescope drive. Did you fix it?' George asked.

'These things get repaired pretty fast, George,' replied Mike. 'Otherwise, we can't survive.'

'You drive the telescope? What do you mean?' I didn't know what they were talking about.

'Yes, of course,' answered Mike. 'Most people don't realize this. Remember, the Earth turns. So, if you want to train the telescope towards a particular star over a period of time, you have to compensate for the rotation of the Earth, don't you? In other words you have to drive the telescope in the opposite direction exactly at the same rate as the Earth's rotation.'

'How do you do that?'

'It is all high-tech, Alfie,' commented George.

'That's right, Alfie,' agreed Mike. 'In the old days some poor assistant had to crank a wheel geared to the telescope and drive it manually. But now, motors do the job. And computers control them. The coordinates of all the stars are stored in the computer. All you have to do is to type in the name of the star you want to observe and the computer takes over pointing the telescope steadily at that star. Let me show you a little more of the telescope and the gadgets we use.'

Mike pointed to a tubular contraption a few feet above the mirror. 'That is where you have the prime focus, the point to which the mirror focuses light,' explained Mike. 'In the old days, astronomers used to have the eyepiece right there. So they used to observe the stars sitting inside the telescope. Or they would attach a camera at the prime focus and take photographs.'

'I remember a photograph of the great Edwin Hubble in his old age sitting inside the Mt. Wilson telescope at the prime focus, Mike,' I said. 'It made me imagine a master musician sitting inside a musical instrument, maybe a gigantic double bass, and producing wonderful music.'

'Oh yes, that is a beautiful photograph, Alfie,' said Mike. 'Even here, there is a cage to sit inside the telescope at the prime focus. We hardly use the contraption nowadays. Instead, with the help of a system of mirrors, light is brought out to the eyepiece outside the telescope. We can then view the stars directly through the eyepiece. But normally, we attach an electronic camera that conveys the pictures to the computer. And the computer stores those pictures and analyses them if necessary.'

'Computer drives the telescope, computer stores the pictures, computer analyses! In other words the computer drives *you*, Mike,' George laughed.

'Don't tell me you don't use a computer for your calculations, George. It drives you too,' retorted Mike and continued his explanation. 'Instead of the camera, Alfie, we can attach a spectrograph that gives the spectrum of a star or of any other source in the sky.'

'Does it use the good old prism to split the light into its basic colour components, Mike?' I asked.

'No, the spectrograph has a diffraction grating built into it,' Mike answered. 'You know that is a piece of glass on which closely spaced lines are etched. It splits the light into the spectrum much better than a prism. Actually, nowadays we use a combination of a prism and a grating, which is called a *grism*. Sounds like some extraterrestrial being, doesn't it?'

'Mike, are you going to show us some stars through your telescope?' asked George.

'Sure, when it gets dark. There is still time for that,' Mike replied.

'In that case, let us get on with the business on hand,' said George. 'You have to tell us how black holes are detected, remember?'

Just as in George's office, neatly tucked away in a corner, was a low circular table with chairs arranged around it and a folding blackboard standing next to it. The astronomers probably discussed their investigations here, as well as the technical problems they encountered. Mike placed a writing pad, a couple of books and some photographs on the table. Obviously he was well prepared to talk to us about the detection of black holes.

'Well, let us see. The basic problem with detecting black holes is that we are looking for the invisible,' Mike began.

'Yes, we know,' George said. 'A black hole only absorbs radiation and does not emit any.'

'So one method of pinning down a black hole is by looking at the company it keeps,' Mike went on. 'It is just like human beings you know. Suppose you meet someone who is strongly influenced by another person whom you may never meet. You could still deduce the nature of the second guy by the behaviour of the first one. In our case we look for binary star systems in which one of the components could be a black hole. There are lots of binary stars in the sky as you probably know.'

'Like Sirius for example,' I added.

'Exactly. Now suppose one of them is a normal, visible star, but its companion is invisible.'

'One moment, Mike,' I interrupted. 'How do you know that this visible star has an invisible companion at all?'

'Good question, Alfie. Suppose you find that the visible star is going round in an orbit. Then there has to be another star, whose gravity holds the former in its path. Simple Newtonian physics. The two would be going around their common centre of gravity. Now, the invisible star could be one of the three end products of stellar evolution. It could be a black dwarf, that is a white dwarf that has cooled off and therefore not shining any more; or a neutron star, or finally a black hole, the beast we are stalking. The three differ from one another. I don't mean in their internal structures, which we cannot determine anyway. But they have different mass ranges.'

'Yes, George explained these things to me some time ago,' I said. 'Let me recapitulate what he told me at the time. A white or black dwarf can have mass only up to the Chandrasekhar limit of about one and a half solar masses. The neutron star limit is a bit more complicated affair since our knowledge of nuclear forces acting within it is not totally complete. The present-day value for this limit is between one-and-a-half to three-and-a-half solar masses. The theoretical estimate under extreme conditions is around four solar masses. Observationally almost all neutron stars, or pulsars, so far detected have masses around the Chandrasekhar limit. So some astronomers feel that any invisible star heavier than two solar masses cannot be a neutron star. The bottom line is that we can have a neutron star with a maximum of, say, around five solar masses. Beyond lies the mass range of black holes. If I am wrong, blame it on George.'

I could see that George was quite pleased with what I had learnt from him.

'You got it all right, Alfie,' Mike assured me. 'So the question is how do we go about determining the mass of the invisible component of the binary system. The answer is by studying the spectrum of the visible star going around its invisible friend. Let me give you an idea of what a stellar spectrum looks like. I have here the spectrum of a single star, our own Sun.'

Mike spread out on the table a photograph of the solar spectrum. Brilliant colours from red to violet were stretched out in a luminous band. Interspersed against this continuous spectrum were a number of dark lines.

'Lovely colours, wouldn't you say?' said Mike. 'But beauty takes a back seat. What is important are the dark lines.'

'The Fraunhofer lines, aren't they?' I asked.

'You are perfectly right,' replied Mike. 'There are about a million of them. They are the fingerprints of the elements present in the solar atmosphere, the comparatively cool outer layers of the Sun. Each element absorbs the same wavelength of radiation from the Sun, as it would emit if it were to be heated. We can study the composition of the stellar atmosphere by analysing these absorption lines.'

'Mike, don't tell us that you detect a black hole from the spectrum of its atmosphere,' George said. 'Both Alfie and I know very well that no such atmosphere can exist. It would be sucked in by the black hole. Of course an accretion disk is a different matter altogether.'

'Actually if such an atmosphere existed enveloping a black hole, it would be like the clothing of the invisible man in H. G. Well's novel, wouldn't it? The clothes made the invisible man's form visible,' I observed. 'The poor man had to go around stark naked in the freezing cold to avoid detection.'

'On the other hand, a perfectly normal star could wear a cloak of invisibility, you know,' Mike said.

'Really? That is interesting. Something I didn't know,' remarked George.

'Oh, yes. A really bright star, hot and heavy, surrounded by dust can remain invisible. For instance, this happens in the case of a binary in the constellation Auriga. Let me show you the constellation, only a picture, not the real thing.'

Mike opened one of the books lying on the table and displayed the constellation. It seems that Auriga, the charioteer, has been widely known since ancient times – from the Babylonians to the Arabs to the Chinese, all identifying it as a charioteer. One cannot identify the chariot, let alone the horses, the way the constellation is depicted. You need a pretty good imagination to visualize them.

'Well, the binary is known as Epsilon Aurigae,' Mike continued. 'One of the two stars carries about eight solar masses. It cannot be seen because of the dust envelope that surrounds it. See, it is invisible and has a mass clearly above the neutron-star limit. So you could easily mistake the impostor for a black hole.'

'Then how do you know it is not really a black hole?' asked George.

'I knew that question was coming,' Mike grinned. 'The visible component is eclipsed for the duration of about two years every twenty-seven years. This is too long a duration to be caused by a black hole of eight solar masses, which would be only some twenty-five kilometres in radius. Therefore the unseen guy is not a black hole at all but possibly a large normal star in disguise.'

'A real red herring then,' commented George.

'All right, so much for impostors and impersonators. Let us get on with the real thing,' said Mike. 'We were talking of a binary system in which one of the stars is visible. Let us say we have its spectrum. Then this is known as a spectroscopic binary. As the visible star goes round in its orbit, its spectrum oscillates about a mean position. I mean it swings between red- and blue-shifts. This is due to the Doppler effect. I don't think I have to explain the Doppler effect, Alfie. I am sure you are familiar with it.'

'We know the Doppler effect,' George declared. 'Alfie here can tell you about all sorts of patent applications he writes up that use the Doppler effect in ways you could never have imagined. But that can wait. Go ahead, tell us what happens with your spectroscopic binary system.'

'All right, the spectrum shifts towards the red when the star is moving away from us and towards the blue when it is approaching us. This happens rhythmically with a definite period. Obviously it is the same as the period of the orbital motion of the star. Also, one can determine the orbital velocity of the star from the Doppler formula for the red- or blue-shift. From this you can figure out the orbital radius by dividing the velocity by the period. You see, at one stroke we got two parameters of the visible star's orbit, namely its velocity and the radius.'

'How about the spectrum by itself? Surely it must tell you something about the star,' prompted George. There was no doubt that he knew all about the detection of black holes. He was just being a good sport in educating me, as was Mike.

'Of course, the characteristics of the stellar spectrum and the brightness of the star are directly related to its mass,' Mike said. 'Which means we can estimate the mass of the visible star.'

'So you have now three pieces of information on the visible star. What do you do with them?' George asked again.

'Essentially we go way back to good old Kepler,' replied Mike. 'We take the equation of motion of the two stars about their common centre of mass. We feed in the three parameters of the visible star, its mass, velocity, and period of revolution.'

'And what do you get?' It was my turn to ask.

'Ah, we get an estimate of the mass of the invisible star!' Mike said triumphantly.

'If it is greater than say five solar masses then you have caught a black hole,' I added.

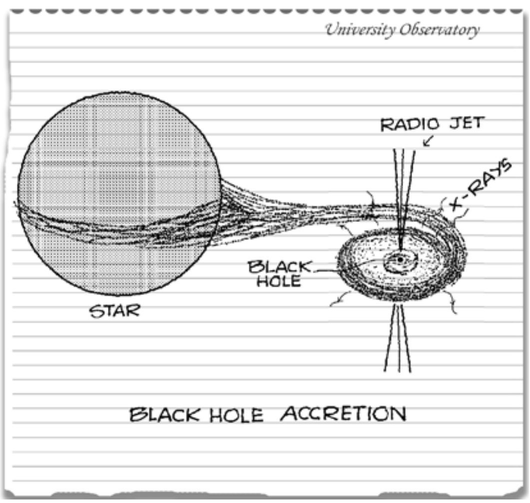
'Exactly. Now you know how a black hole in a spectroscopic binary is detected.'

'Let us drink to that,' George raised an imaginary glass. 'Have you guys found any such black holes stealthily hovering around visible stars?'

'Well not us guys, none of us here is a black-hole hunter I am afraid. But other astronomers have pinned down black holes by the method I outlined,' replied Mike. 'Nearly a dozen of them have been detected. The first and the foremost among them is called Cygnus X-1.'

'Why that name?' I wanted to know.

'The star system we are talking about is in the constellation Cygnus, the Swan. Furthermore, it is an X-ray source. So the nomenclature Cygnus X-1.'



'What has X-rays got to do with the black hole? After all, the thing doesn't emit any kind of radiation.' I thought this was obvious.

'True, Alfie, true,' Mike said. 'It is not the black hole that emits the X-rays, but the accretion disk around it. I assume that George has told you about accretion disks around black holes.'

'We have touched upon that, yes,' George answered. 'The disk is formed, as you know, Alfie, by matter streaming in from the star that accompanies the black hole. The disk can get heated up to millions of degrees because of friction as the gas rushes towards the black hole. At these temperatures the gas emits X-rays. An X-ray source does not automatically qualify as having a black hole though.'

'I understand,' I said. 'In Cygnus X-1 you had an X-ray source which had to be identified with a binary containing a black hole. Am I right?'

'Absolutely, Alfie,' affirmed Mike. 'The location of the X-ray source coincided with that of a well-known visible star. This star had been classified as a hot blue giant of around twenty-five to forty solar masses. It was suspected that the X-rays were due to accretion of matter from the blue giant onto an invisible compact star. So the spectrum of the giant was analysed and, as suspected, it had an invisible companion, the two forming a spectroscopic binary. And we have seen how the mass of the unseen star could be estimated. It turned out to be at least seven solar masses. The astronomical detective squad had thus nabbed their first black hole!'

It was true, the whole black-hole hunt sounded like a detective story. Circumstantial evidence had pointed its finger directly at the culprit. Well, I take back my statement, since I don't think a poor black hole qualifies to be a criminal.

'The study of accretion disks has become an important field of research in its own right, you know,' George pointed out. 'Many detailed theoretical models have been proposed taking into account all sorts of possible physical effects. From such models one can compute the X-ray spectrum. You can then compare it with the actual observational data. Interestingly enough, one can possibly tell whether the central collapsed object attracting matter is a neutron star or a black hole.'

'How is that?' I asked.

'If you remember, Alfie, we discussed earlier the striking difference between a neutron star and a black hole,' George proceeded to explain. ' A neutron star is a solid body, whereas a black hole is a sink that drains everything away. Often, the heat generated in the accretion disk is carried along by the gas streaming towards the central object instead of simply radiating it all away. This is called *advection*. Suppose now that the central object is a neutron star with a solid surface. Then it too gets heated up by the hot accreting matter and radiates in turn. On the other hand, all this heat would simply go down the drain if there were a black hole sitting at the centre. Because of this, the spectra in the two cases differ quite distinctly. So, you see, you could tell what kind of animal you have trapped.'

'All this is terribly interesting,' I observed. 'I see that theory and observation work closely hand in hand. But of course all the evidence for the black hole is circumstantial, isn't it?'

'You are right, Alfie,' Mike affirmed. 'After all the black hole is not like an ordinary star that can be observed directly.'

'For that matter, you do not see an elementary particle directly either, do you?' George pointed out. 'We can only observe its effects on its environment. For instance, an elementary particle can leave a track in its wake in photographic plates or within bubble chambers. But, of course, there is a difference. In astronomy we have no control over the objects we observe. It is quite different in the case of elementary particles, isn't it? There you can choose the experimental set-up in your laboratory. And even manipulate the particles you want to observe.'

'Tell me something,' I continued my queries, 'There are all these stellar-mass black holes that have been detected in binaries. I suppose they belong to our own Milky Way galaxy. Am I right?'

'Absolutely,' Mike confirmed.

'But the daddy of them all is sitting right at the centre of our Milky Way,' George remarked. 'A giant weighing millions of solar masses.'

'I know,' I said. 'Nowadays you read about these things in newspapers. How true is it?'

'True enough, astronomers are now convinced that such a black hole is lurking at the centre of the Milky Way,' Mike responded. 'The history of this galactic Gargantua dates back to the very beginning of the nineteenth century, you know. In the late eighteenth century Laplace had thought of invisible stars. You know about it, don't you, Alfie?'

'Oh, yes, George told me about it in detail,' I answered.

'In 1801, the German astronomer Johann Seldner suggested that an enormous invisible star like Laplace's might be hiding at the galactic centre. He said that this would lead to the rotation of the galaxy.'

'What happened to that idea?' I asked.

'Well, Laplace abandoned his idea of an invisible star as too outlandish, didn't he? In the same way Seldner gave up his speculation since such a hidden star had to be unimaginably massive.'

'A sound prediction thrown away,' said George. 'Of course, the idea has been resurrected in our own time.'

'We have to take a look at the centre of our Milky Way to track down the invisible giant hiding there,' Mike said. 'You know how difficult it is nowadays to see the Milky Way from within the city limits. Much too much light and dust. But out here it looks so beautiful, a wispy band, consisting of a mysterious soft glow stretching across the sky. All the stars we see in the night are inhabitants of the Milky Way.'

'And so are we,' added George. 'It takes some imagination to realize that our own Solar System belongs to the Milky Way.'

'It takes much more than imagination to prove it,' commented Mike. 'Over the years, astronomers have learnt so much about our own galaxy. It is amazing.'

'Let me tell you what I know of the Milky Way to save your breath,' I volunteered and went on to describe whatever I knew about our galaxy. 'Our galaxy is in the shape of a disk with a central bulge. It consists of spiral arms made up of stars and dust. The Milky Way is about one hundred thousand light-years across. We are tucked away at the outer edge at a distance of two-thirds its expanse measured from its centre. The entire galaxy rotates and the Solar System takes some two hundred and thirty million years to complete a revolution around the galactic centre. The last time the Solar System was where it is now, dinosaurs roamed the Earth.'

'That is a pretty good description of our galaxy, Alfie,' said George appreciatively.

'Yes, indeed, Alfie,' Mike nodded. 'Now, the centre of our galaxy lies in the direction of the constellation Sagittarius. Let me show you that constellation.'

Mike opened the book of constellations and showed us the picture of Sagittarius, the celestial Archer, poised to shoot an arrow towards the heart of Scorpio.

'Sagittarius is a centaur, the mythical beast, which is half human, half horse.' Mike described the constellation. 'In the Greek tradition, centaurs were in general rude, cheating, untrustworthy, violent, and drank too much – in other words, more human than beastly. Sagittarius, or Chiron as he was called, was an exception. He was kind, gentle, wise, and skilled in many ways. Among his many illustrious pupils was the mighty Hercules.'

Mike closed the book of constellations and picked up another book.

'Here is a photograph of the Milky Way in the direction of Sagittarius,' Mike displayed a glossy, colourful picture. It was a beautiful photograph with stars and star clusters as well as dark patches in between.

'The centre of our galaxy is obscured by large clouds of gas and dust as you can see,' Mike explained. 'Optical telescopes cannot always be used for the exploration of this region. Fortunately, electromagnetic radiation at other wavelengths – radio waves, infrared radiation, and X-rays – can tell a lot though. What we call the galactic centre is roughly thirty light-years in diameter. The total luminosity of this region, adding up the contribution at all wavelengths, is about ten million times that of the Sun.'

'Why should we suspect the existence of a black hole in such a luminous region then?' I asked.

'Because gravitational collapse into a black hole is most likely where there is a lot of mass, that is why. And the greatest concentration of matter happens to be at the centre of a galaxy,' answered Mike.'

'All right, let us say there is an enormous black hole hiding behind the dust clouds over there. Do you track it down once again by its influence on the surrounding objects?' I asked. Probably it was a redundant question.

'Yes, but in addition, the black hole by itself is trying to announce its existence you know,' replied Mike. 'At the very heart of the Milky Way, astronomers have discovered the strongest source of radio waves in the entire galaxy. Its radio luminosity is ten times greater than the Sun's optical luminosity. But it is extraordinarily compact, just the size of a large star, say a red giant.'

'Where do the radio waves come from then?' I asked.

'From the matter being swept up by the black hole,' Mike answered. 'The black hole is in the process of accreting matter in its vicinity at a slow rate. Entire stars could be shredded by the tidal forces of the black hole and sucked in. Because of the slow rate, not enough heat is generated to produce X-rays. Only radio waves are emitted.'

'Is this all the evidence you have for the black hole? 'The evidence for a black hole did not seem to be too strong to me.

'Aha, you are suspicious of us astronomers, Alfie,' Mike wagged his finger at me. 'There is far more influence of the black hole on the surrounding matter. To see this, we must enter the infrared region of the spectrum. Satellites have been sent up carrying infrared detectors. And they have found gas clouds at the galactic centre heated up to a few hundred degrees. At such temperatures, these molecular clouds emit infrared radiation. From observations in the infrared, one can determine the radius of the orbit of the gas clouds. What is more, one can measure the speeds of these clouds as they go around the centre. That is done using the Doppler-shift method. Anyway, the bottom line is this. From these observations, one can estimate the central gravitating mass using the formula good old Kepler gave.'

'That's very interesting, Mike,' I said. 'So how big is the central mass?'

'It turns out that the central mass is about three million times that of the Sun, confined within a radius of a tenth of a light-year. A huge mass concentrated in a very small region indeed. The natural conclusion is that it is a super-massive black hole.' After a momentary pause Mike added, 'That is not all.'

'You mean there is more to the story?' I asked.

'Of course, Alfie, in astronomy, as in other areas of science, there is continuous progress. And I can tell you a more recent development related to this giant of a black hole,' Mike continued with his exposition. 'Using special techniques, ground-based infrared observations have also been made with high accuracy. And these observations also support rather strongly the existence of a black hole at the galactic centre. As a matter of fact, stars have been observed going round the galactic centre in elliptical orbits. For instance, one of them zooms around at a speed exceeding five thousand kilometres per second.'

'Is that very fast?'

'Oh, yes, compare it with the lazy Earth, which ambles around the Sun at the rate of a mere thirty kilometres per second,' Mike said. 'What is striking is the star's distance from the centre. It is just seventeen light-hours at the point of closest approach. And the estimated mass within this radius is at least two million solar masses. There you are. You are left with no alternative but an enormous black hole sitting at the galactic centre.'

'Why can't it be something else, say a whole bunch of invisible compact objects like neutron stars?' asked George.

'A rhetorical question I take it, since you know the answer very well, George,' responded Mike. 'If you were to pack so many neutron stars into so small a space, inevitably they would collapse into a black hole. So the conclusion seems to be inevitable. We are stuck with a gigantic black hole presiding over our galaxy.'

'Mike, what is so special about our galaxy?'

'What is so special about the Milky Way, Alfie?' George intervened. 'Why, you, me and Mike are all in it!'

'George, that is a highly egocentric view of the Milky Way,' I retorted. 'What I meant was what is so special about our galaxy that it harbours a giant black hole. How about other galaxies?'

'You are right, Alfie,' Mike agreed. 'There is nothing special about our Milky Way. Almost all galaxies seem to harbour super-massive black holes too.'

'How do you know that?' I asked.

'Well, one comes to this conclusion once again by observing the motion of matter around the centres of other galaxies. There is one more technique, which is highly accurate in studying the motion of matter around the galactic centre. This involves maser emission. Alfie, I am certain you know what masers are.'

'Sure thing, Mike. Masers are the radio-wave version of lasers,' I replied. 'Do you use them as part of your observational equipment?

'No, Alfie, but believe it or not we are talking about celestial masers that act as sources of radiation,' Mike said smiling at my obvious surprise. 'They are quite small in size, so precise measurements can be made on their motion. Condensations of water vapour for instance, or cloudlets as they are called, produce water-maser emission. In essence, you have bright point sources, whose motion can be traced very well indeed. And again, from these observations, one can estimate the mass of the black hole at the galactic centre.'

'All right, tell me about black holes in other galaxies then,' I said.

'Let me give you a couple of examples,' Mike went on. 'Take for instance the one in our own neighbourhood, the galaxy in the constellation Andromeda. It too contains a black hole weighing some ten million solar masses. Then there is this famous galaxy known as M87.'

'Sorry to interrupt you, Mike,' I said. 'Forgive my ignorance. Why M and what is the significance of 87?'

'No problem, Alfie,' assured Mike. 'The letter M stands for the eighteenth century French astronomer Charles Messier. He catalogued about a hundred brightest non-stellar objects in the sky that are known as Messier Objects. And 87 refers to the number in his catalogue. Now guess how massive the black hole might be at the centre of M87.'

'Maybe twenty-five million solar masses?' I took a random shot placing the mass on the higher side.

'No, Alfie, it weighs around three billion solar masses!' Mike announced.

'That is incredible!' I exclaimed genuinely surprised.

'Isn't that mind-boggling, Alfie? A black hole so heavy!' said George.

It was indeed unimaginable. There are these billions of galaxies spread out all over the universe. Hidden deep within the hearts of most of them lurk gigantic black holes, each brooding in anticipation of an unsuspecting star that may stray into their ambit of terminal attraction. And having captured one, they shred and swallow it, growing larger in size.

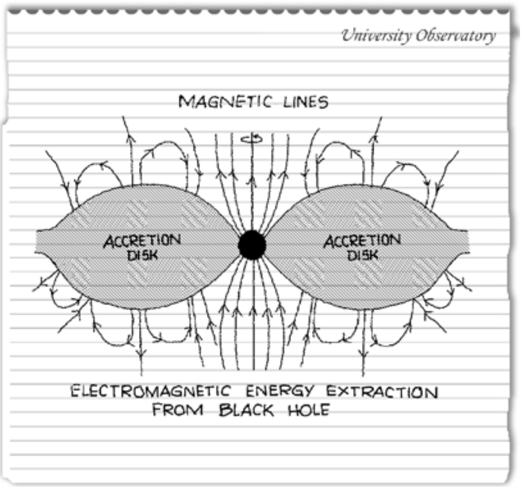
'What we have at the centre of our own Milky Way and within the Andromeda galaxy are comparatively calm, quiet black holes with no accretion disks around them to write home about, just some tenuous gas flowing in,' continued Mike. 'On the other hand, there are galaxies with vigorous accretion disks around their central black holes. Streams of gas rush in violently, swirling and rubbing against one another, generating immense amounts of heat by friction. They create active galactic nuclei, or AGNs as they are called.'

'Do these galaxies appear different from ours or the one in Andromeda? I mean when you make your astronomical observations of them.'

'Oh, yes indeed! For instance some of these, called radio galaxies, are strong sources of radio waves that emerge from the accretion disks. That is not all. There are those like the one in the constellation of Centaurus, known as Centaurus A. It is the nearest radio galaxy to us, at a distance of about sixteen million light-years. This galaxy ejects tremendous jets of ionized gas in opposite directions. These radio jets from the centres of galaxies can extend anywhere from thousands up to nearly a million light-years. They end up in huge clouds, or lobes as they are called.'

'You mean the length of these jets can be nearly ten times the width of our Milky Way! There must be a lot of energy involved in these processes,' I surmised.

'Naturally! First of all, the energy output from the AGN itself is so prodigious, that it can be brighter than a trillion suns. The energy radiated by the jets is about ten per cent of this. From the velocity of the gases in the jet and its length, one can estimate the time of its ejection from the centre or its age. This turns out be a million years or so. So, enormous amounts of energy must have been radiated away by the AGN and pumped into the jet during all this time.'



'How are these jets produced, Mike?' I asked. All this was absolutely fascinating.

'Ah, maybe George should explain,' replied Mike. 'After all, it is the theoretician's job to build models.'

'Passing the buck, eh Mike?' responded George. 'All right, it is a very complicated business, these radio jets. Let me give just the basic ingredients of it. All gases in astronomical set-ups carry some magnetic field. The gases streaming out of a star and forming the accretion disk is no exception. Furthermore, because of its high temperature, the gas is completely separated into a sea of positive and negative charges, or a plasma as it is called. These rotating charges in the plasma can also produce magnetic fields. Not only that. Magnetic fields can be attached to the rotating black hole itself. The end result of all this is that the rotation of the black hole, in combination with the magnetic field, generates immense electric power, as in a gigantic dynamo, which propels the charged gas along the magnetic field lines. Some astronomers believe that, by considerations of symmetry, this gas must come out as jets aligned along the rotation axis of the black hole in opposite directions. As I said before, all this is too complicated, Alfie. And I am afraid the details of this process are not well-understood at all.'

'Ah, as for the power generation, it is back to Faraday and his electromagnetic induction on a cosmic scales then! Where does the energy for all this come from, George?' I asked.

'From the rotation of the black hole, of course, Alfie,' answered George. 'Remember we are dealing with supermassive black holes of millions or even billions of solar masses. They store up enormous amounts of rotational energy. And what we have here is the electromagnetic extraction of that energy. This and the gravitational potential energy of the accreting matter both may act as a source of energy for the luminosity of the radio source. But the ejection of jets seems to be solely due to black hole's rotational energy since the direction of the axis is involved.'

'There is another example where a massive black hole, together with an accretion disk acts as the central engine,' Mike took over. 'This is in the case of the energy production in the quasar. I am sure you know about quasars, Alfie.'

'Roughly. The name quasar stands for quasi-stellar radio source,' I said. 'Quasars look like stars because they are quite compact and are at cosmological distances. They must be extraordinarily powerful sources of radiation to shine as they do in spite of such enormous distances. Am I right?'

'Quite right. In the case of a quasar, the accretion disk is phenomenally active, producing intense radiation. As a result, the rest of the galaxy may not be visible at all. Radiation emitted by all the stars in the galaxy is swamped by that of the central engine. So, you can see only the compact region around the black hole furiously radiating away energy. However, galaxies associated with the quasars have been detected in some cases.'

'You seem to be pretty sure of things happening millions of light-years away, Mike,' George remarked with a smile.

'Thanks to theoreticians like you, George,' Mike countered. 'Alfie, we observers record honestly what we see. And the Georges of this world build models to explain our observations. Between you and me, Alfie, if we find something new, they change their model to suit the new findings.'

'I protest,' George said with a broad grin.

'In any event, all observations of galaxies seem to confirm the black-hole accretion model for the central engines that may exist at galactic centres,' Mike stated with finality.

'Let me ask you a basic question,' I said. 'The huge amounts of energies we are talking about are of gravitational origin, aren't they?'

'Absolutely,' Mike concurred.

'I thought gravitation was the weakest force in nature. How come it produces so much energy then?'

'On a cosmic scale, Alfie, gravity is king. It rules the universe,' observed Mike. 'Electromagnetism is more or less out, since matter on the whole is neutral. Neutron stars, or equivalently pulsars, come with very high magnetic fields, no doubt. These magnetic fields play an important role in the emission of radiation. But they can in no way produce energies of the order that is required for active galactic nuclei.'

'How about nuclear energy? After all it fuels the shining stars.'

'Even nuclear energy loses out to gravitation,' replied Mike. 'The crucial factor, Alfie, is the efficiency of energy production. As it turns out, nuclear transformations have rather low efficiencies. For instance, we know that in the interiors of the stars hydrogen is converted into helium, releasing energy in the process. Suppose you take a kilogram of hydrogen. Only about ten grams or less of it are converted into helium. In other words, the efficiency here is less than one per cent. On the other hand, let us take the case of gravitation. In particular, we are dealing with the gravitational potential energy of the streams of gas in the accretion disk, spiralling down into the black hole. One can compute the potential energy released in this case. And it happens to be equal to more than ten per cent of the matter falling into the black hole. This is why we need a black hole surrounded by an accretion disk. Only such a model can explain the fantastic amounts of energy needed to create the radio jets or make the quasars radiate.'

'Death and transfiguration,' I remarked.

'That is the title of a composition by Richard Strauss, isn't it?' Mike asked somewhat puzzled. 'How does that come into the picture?'

'Well, what I mean is that here is the black hole, the sombre end product of stellar evolution, all absorbing, radiating nothing. It represents death. Yet, it also engenders, through the phenomenal activity occurring in its exterior, the radiance of a trillion suns. And that is the transfiguration.'

'You are perfectly right, Alfie,' Mike nodded. 'It *is* an amazing metamorphosis.'

After a moment's pause, Mike added, 'You know, Alfie, I have outlined very briefly some basic methods of detecting black holes. There are plenty of details I have left out. Moreover, there is always the latest development in this fast-growing field.'

'You have done a fine job, Mike,' said George with warm appreciation. 'We will soon have another occasion when you can tell us the hottest news straight from the oven, so to speak. I would very much like my three students to be around when you do that.'

'Mike, all the evidence for the existence of the black hole seems to be indirect, circumstantial,' I pointed out. 'Isn't there *any* phenomenon at all in which one can see the mark of the black hole a little more directly?'

'Yes, I think there is. Gravitational radiation. Yet to be detected on the earth,' answered Mike.

'Why don't you tell us about gravitational waves, pinning down black holes, Mike?' suggested George.

'Oh, no, I am only a poor observational astronomer,' declared Mike. 'What has not been observed falls outside my department, but belongs to George's. George, why don't you tell us how to detect black holes through gravitational waves?' And turning to me, he asked, 'Alfie, has George told you about gravitational waves?'

'Yes, he has,' I replied. 'Now and then, here and there. He touched upon the subject when he told me about general relativity. Then again, he discussed some aspects in the context of black holes. He outlined the perturbation theory and, in particular, described the quasi-normal modes. But he promised to tell me more some time or the other.'

'Aha, my grandma used to say that a promise made is a debt unpaid,' remarked Mike. 'George, pay up your debt. Tell us about gravitational waves and how they could be used in the detection of black holes.'

'All right, wise guy, I shall keep my promise,' began George. 'As we know, gravitational waves are ripples in the fabric of spacetime. They can be generated by the motion of matter in general, say by two vibrating masses connected by a spring or a rotating bar. Any terrestrial source you can think of would be of no use. The waves it could possibly produce would be extremely weak.'

'You mean gravitational waves are not like electromagnetic waves,' Mike put in. 'Hertz could generate and detect them right in his laboratory.'

'Exactly. Therefore we have to think of astronomical sources. They can be expected to produce gravitational radiation on sufficiently large scales so you can detect them here on the Earth.'

'One moment, George,' I interrupted his exposition. 'Is there any evidence for the existence of gravitational waves at all? I mean at least within the context of astronomical observations before one can think of detecting them on the Earth?'

'Excellent question, Alfie,' George said. 'The answer is yes. There is an extraordinary binary system in the constellation Aquila, the Eagle. And it has demonstrated the existence of gravitational radiation. This binary system consists of an invisible star, a neutron star, and a pulsar going around each other. The pulsar emits about seventeen pulses per second with extreme regularity. It acts as a highly accurate clock, in fact as accurate as an atomic clock. The two stars are circling around each other at breakneck speed, with a period of only seven hours and forty-five minutes. They are in an amazingly close orbit of a few million kilometres. The gravitational field at such a close separation is quite high. What does that mean?'

'It means that general relativity comes into full force,' I answered.

'Precisely,' George continued. 'Now the pulsar clock can be used to measure the orbital period quite accurately. Meticulous observations on the binary were carried out for more than a decade. And those observations revealed that the orbital period was decreasing or, in other words, the two objects were speeding up. This happens if the orbits were shrinking. That also meant that their total energy was diminishing. Why should this happen? Why should the stars be losing energy like this?' George paused, expecting the answer from me.

'Because the two stars orbiting each other must be emitting gravitational radiation,' I answered.

'You got it, Alfie,' affirmed George. 'One could calculate the rate at which the energy was being lost by the binary system. This could be done from the data on their orbital dynamics. At the same time, one could also compute the energy carried away by the gravitational waves emitted by the binary system. For this, the good old formula Einstein himself had derived came in handy. And what did one find?'

'One discovered that the two estimates tallied wonderfully well,' I supplied the expected answer with a smile, anticipating the customary remark from George. I was not disappointed.

'Amazing, how did you guess, Alfie?' chuckled George while Mike grinned. 'This tallying demonstrated the existence of gravitational waves. Quite firmly, you know. For this work two radio astronomers, Joseph Taylor and Russell Hulse, were awarded the Nobel Prize. Now let us follow the future of the binary as it unfolds. The two stars come progressively closer, as their energy is carried away by the gravitational waves, and they orbit faster and faster. The emission of gravitational radiation too keeps going up. Finally, in about three hundred million years or so, the two neutron stars coalesce, giving out a burst of gravitational radiation as a grand finale.'

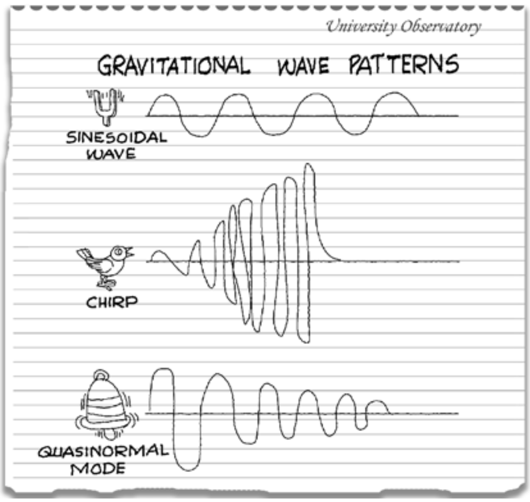
'Can you follow the details of this courtship of the two neutron stars and their explosive marriage?' I asked.

'You mean theoretically? Yes, in fact it has become a field of intense research in its own right,' replied George. 'On the one hand, one has to follow the dynamics of the neutron stars in motion. On the other, one has to continuously determine the emission of gravitational waves. Let me tell you, it is a quite complicated affair.'

'How do black holes fit into this scenario?'

'Well, just like two neutron stars we can think of two black holes going around each other, can't we?'

'Then you do exactly the same kind of calculations as in the case of neutron stars?'



'In principle, yes. But both setting up the mathematical framework and the actual numerical computations are much more complicated. Ultimately one would like to get the details of the emitted gravitational waves as the black holes come closer to each other and finally merge together. From this data one could find out a lot of information about the dynamics of the black-hole coalescence as well as the emission of gravitational radiation. For instance, when the binary components are far apart, the wave is essentially a regular sinusoidal wave. When a tuning fork vibrates, it emits such a sound wave, doesn't it? The frequency increases slowly at first, as the orbits of the black holes shrink due to the emission of gravitational waves. However, as the two black holes come very close to each other, they emit gravitational waves with steadily increasing amplitude and frequency. This wave pattern is called a *chirp*, like that of a bird. And in the final stages of coalescence, the quasi-normal modes emerge resembling the pure dying notes of a bell. And they carry the unmistakeable signature of the black hole.'

'All this is grand, George,' intervened Mike. 'But how does one detect gravitational waves in the first place. Tell us that, would you?'

'Guiding me in my sermon, eh, Mike?' George looked at Mike, raising his eyebrows. 'All right I shall tell you briefly, essentially the basic principles. First, how do we generate and detect electromagnetic waves?'

'Simple enough, when a charge, say an electron, jumps up and down, I mean oscillates, it produces electromagnetic waves,' I answered. 'When the electromagnetic wave hits another charge, it sets the latter in motion too. The effect can be detected by the retina of the eye or any other device,' I answered.

'Fine. Now, gravitational radiation is produced by the motion of matter, as we have already discussed. Just as electromagnetic waves set a charge in motion, gravitational waves would, in principle, make matter move. For instance, if I move my hand up and down like this, it would produce gravitational waves. If it hits your hand, your hand should move up and down too. But it won't because the waves are extremely weak.'

'Thank heaven for that,' Mike interjected. 'Especially since George gesticulates a lot when he lectures. Can you imagine his whole class gesticulating too, in unison with George?' Mike threw back his head and laughed.

'Very funny,' said George with his ready smile appearing on his face. 'Even the most powerful wave sources would produce just minute tremors in any kind of detecting device stationed on the earth. The first detector was simply a big cylindrical bar hung by piano wires. It was painstakingly shielded from all disturbances. Joseph Weber, who is acclaimed as the pioneer in the field, built it. He started it all against tremendous odds you know. The vibrations of the bar were expected to be of nuclear dimensions.'

'That small? How do you detect such absurdly minute disturbances?' It seemed to be a hopeless task.

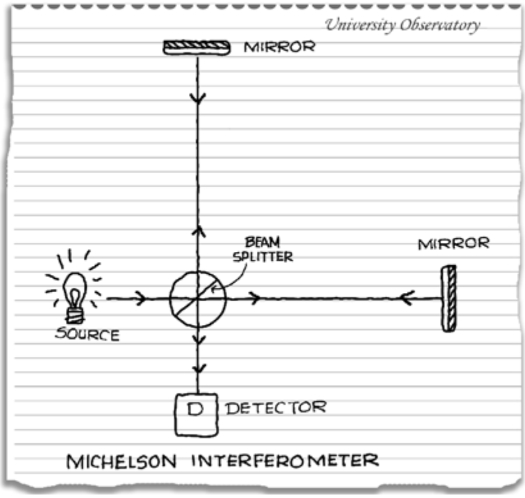
'Weber used piezo-electric devices which generate electric currents under mechanical stresses. These currents were amplified and recorded to see whether any gravitational waves were producing tremors in the bar.'

'Did Weber detect the waves then?'

'Well, he reported that he had received signals,' said George. 'But, unfortunately, Weber's findings were not confirmed. Since then other more sensitive bar detectors have been set up. So far they haven't detected any waves either. Now there are other detectors that work on the principle of optical interferometers.'

'You mean they employ a different principle than the bar detectors?'

'The rock-bottom principle is the same, Alfie. The waves make something move and you have to find this movement. But the technique of detection is



different. The detectors are essentially scaled-up version of the Michelson interferometer that was employed to detect the ether wind, which, of course, didn't exist. Mike, pass the writing pad please. Let me draw the interferometer for Alfie.'

George sketched the Michelson interferometer for me.

'I don't want to go into the details, Alfie, just the basic principle. Light from the same source is split into two perpendicular beams of equal lengths. These are called the two arms of the interferometer. Now they recombine at the detector after being reflected by two mirrors. As you know I am sure, two light waves can interfere. That is, where they add up they produce a bright band of light and where they cancel each other you find a dark band. The location of the interference fringes, as the alternate bright and dark bands are called, depends on the arrival time of the light at the detector. In their original experiment, Michelson and Morley aligned one of the arms along the motion of the Earth and the other perpendicular to it. The speed of light along the former would be that along the perpendicular arm minus the speed of the Earth. That is, provided there was an ether wind blowing. Now suppose the arm along the Earth's motion were to be reversed. Then the speed of light in its direction would be the speed in the perpendicular arm plus the speed of the Earth. This change in the speed of light would have shown up in a shift in the interference fringes, because the arrival time of light along the arm parallel to Earth's motion would have been altered in the two settings. No such fringe shift was observed, thereby proving the constancy of the speed of light and the non-existence of ether. Do you follow, Alfie?'

'Yes, but how does this help in detecting gravitational waves?'

'Well, if the lengths of the two arms differed, even then the signals would arrive at different times, wouldn't they?' George elucidated. 'When a gravitational wave passes the interferometer, it makes the two mirrors move. Therefore the arm lengths change, however minute the change might be. And this can be detected through the shift in the interference fringes.'

'Is it that simple?'

'In principle, yes, Alfie,' answered George. 'But in practice, it is an enormously difficult task. On the other hand, technology has progressed tremendously since Michelson's time, hasn't it? So this task has become feasible to accomplish after all.'

'All this just to catch a few vibrations?' I asked incredulously.

'A few vibrations that will establish a new kind of astronomy, Alfie!' George stated emphatically. 'The hope is that the gravitational waves will tell a tale that will shed new light not only on black holes but on the universe itself. You see, electromagnetic radiation cannot penetrate through the hot plasma that made up the primordial fireball at the very beginning of the universe. But gravitational radiation can. With gravitational waves we should be able to reach out through space and time to the very birth of the universe. It is a grand dream, Alfie.'

There was silence. I looked out of the window. It was late evening and quite dark outside. I felt excited at the prospect of having a glimpse of the night sky through the telescope.

'I noticed, Alfie,' said Mike who was watching me. 'Yes, the time has come to wake up the Mistress of the House.'

Mike silently led us to another corner of the observing floor, where there was a whole bank of computers and a control panel. He flicked a switch and soft music flooded the chamber. Long ago, I had seen a documentary on one of the giant telescopes in which one of the senior astronomers explained how, during the long lonely vigil through the night, often in freezing cold, music sustained the spirit of the observer. Mike turned another knob and the music blared out in heraldic intensity. At the same time the dome above opened up with a rumbling sound, like distant thunder issuing forth from two parting clouds, and revealed the dark night sky. Myriad stars, more than I had ever seen before, sparkled in splendour. And the telescope rose and turned majestically, knowing exactly where to look, and stopped.

Mike detached the camera from the eyepiece and beckoned us to take a look. I saw on his face the same expression of reverence I had noticed when we entered the chamber where the telescope stood. I peered through the telescope, which was focused on the planet Saturn. I could see the beautiful rings girdling the planet. After George had his turn, Mike again steered the telescope in another direction. As I placed my eye against the eyepiece I was greeted by the Orion Nebula, the enormous expanse of gas cloud seething like curling flames, in which clumps of gas and dust condensed and stars were born. Finally at Mike's command, the telescope turned again. This time it was a breath taking sight of a globular cluster made up of some ten to one hundred thousand stars, a swarm of iridescent bees, hovering in space in a spherical formation around a common centre. 'If you do not see gravity at work here, then you have no soul,' Richard Feynman had written about such a stellar assembly.

'Let us go out and take a look at the sky in all its glory,' Mike said and led us to the catwalk that went round the dome. Glittering stars enveloped us in every direction now. As we went round the catwalk, Mike stopped suddenly and stared in front of him.

'Do you see that constellation?' Mike asked as he pointed at a group of stars. 'That is Cygnus, the Swan, in its eternal downward flight with outstretched wings. So many cultures have seen those stars as some bird or other, including the horned owl and the ibis. The Arabs called it Al Tair al Arduf, the Flying Eagle, and then again Al Djajah, the Hen. The Egyptians of three hundred BC saw a hen too. But to me it is always the Swan, lamenting the death of a friend till the end of time.' Turning to me he added, 'And the Swan hosts in its neck an ancient star, that shone through its life and died like the Swan's friend. It embodies, as you said, death and transfiguration.'

As we were about to take leave of Mike, I felt that I had missed out something in all our discussion. I turned to Mike and said, 'Mike, I completely forgot to ask you something I would very much like to know. What kind of work do you do up here?'

'Good that you forgot, Alfie,' laughed Mike. 'Otherwise I would have kept you here all night telling you about my work. My collaborators and I do extragalactic astronomy, related to the structure of the universe. I am sure you will be soon discussing the cosmos with George. Then I shall tell you all about what we do up here.'

'Mike, why don't you come down with us and have a drink?' invited George.

'Wish I could, George,' Mike answered. 'It is a clear night which I can't miss. Tonight none of my colleagues will be coming up. And I can get a lot of observation done. Don't forget, George, you have invited me to join your gang for dinner. I wouldn't miss it for the world. Take care, both of you, and see you soon.'

George and I drove back to the city, winding our way down the hill in brooding silence. I do not know what thoughts were drifting across George's mind. But I was thinking of Mike sitting way up in his sanctuary, all alone through the night, conversing with the stars.

Chapter 17

CELESTIAL SWAN SONG

This story, like all other stories of gods, is timeless. For, the gods themselves are timeless. This story, like all such stories, has been told and retold by mortals for ages past. Like all such stories, different versions varying from one another in minor details have come down to us, but their essence is the same.

Helios, the god who personified the Sun, lived in a palace of utmost grandeur near Colchis in the Far East, way beyond Ethiopia. Every morning he rose from a swamp formed by the meeting of river and ocean. Harnessed to his golden chariot, a carriage so dazzlingly bright that none could look upon it without going blind, were four white winged horses, four fiery chargers whose flaring nostrils breathed fire. Holding the reins firmly in his hands, Helios climbed the vault of the heavens. Thus have the poets sung his glory: drawn in his swift chariot, he shed light on gods and men alike; the formidable flash of his eyes pierced his golden helmet; sparkling rays glinted from his breast; his brilliant helmet gave forth a dazzling splendour; his body was draped in shining gauze whipped by the wind.

At midday the resplendent god reached the zenith of his course and then began his descent towards the West. At the end of the day, he arrived in the land of the Hesperides, where he appeared to plunge into the ocean. But in reality, Helios had reached another palace he owned in the Far West, near the Elysian Fields. There he un-harnessed his team of horses and let them roam freely, grazing on magical herbs. Then he loaded them, along with his chariot, onto a golden ferryboat. Fast asleep, exhausted as he was from his daylong journey, he sailed all night around the world by way of the Ocean Stream until he reached Colchis again.

As befitting a god, Helios boasted several wives as well as other loves, all those whom he had acquired in the course of his daily travels. Among them was Clymene, wife of Merops, King of the Ethiopians, by whom Helios had seven daughters, who were called the Heliads, and a son named Phaethon.

One fateful day, Phaethon had a dispute with Epahus, son of Zeus and Io, because Epahus had cast doubts on Phaethon's divine origin. Mortified beyond measure, Phaethon went to his mother and related his unbearable plight to her. Clymene advised her son to approach Helios himself and have his divine birth confirmed. Phaethon set out on his arduous journey travelling far beyond Ethiopia, far beyond India, and after many months finally arrived at the palace of Helios. The father was ecstatic to see his son, whose very name, that meant radiant like the sun, bespoke of his brilliant aspect. Phaethon appealed to his father to accord him a favour, which would prove to one and all that he was indeed the son of the sun god. As any doting father would, Helios readily acceded to this request and swore by the river Styx that he would indeed be happy to grant any wish his son might express.

After a moment's thought, Phaethon asked permission to drive sun's chariot across the sky for one day thereby demonstrating to all eyes that he was indeed the son of the great god Helios. Taken aback by this unexpected request, Helios tried in vain to dissuade the impetuous youth from his proposed hazardous endeavour. Phaethon persisted and Helios had no choice but to yield as he had taken an irrevocable oath to grant his son's wish. Thus it came to pass that Helios had to consign his golden quadriga to the control of his rash son.

The next morning the chariot was prepared and the four fierce horses were harnessed. Phaethon, jubilant and proud, set out on his venture ignorant of the fearful dangers that awaited him. 'Be careful, son,' cautioned the anxious father. 'Hold on to a middle course between Heaven and Earth, do not veer to the edges of the sky,' Helios shouted out his advice to his departing son, alas, to no avail. For, the eager son failed to hear the words of wisdom his father had spoken as he took off on his journey in haste. The spirited steeds, which had rested during the night and were rearing to fly around the heavenly vault, leapt forth into the sky. It took no time for the horses to realize that inexperienced hands held the reins now. They flew free and wild not heeding the feeble control Phaethon tried to exercise and rose far above their normal course. As they thundered across the sky dome, shaking the very foundations of the firmament, the overheated wheels of the chariot scorched a shimmering streak in their wake that came to be known as the Milky Way. At the same time, since the chariot of Helios was so high in the sky depriving the earth of sun's heat, icy chill spread over regions directly below, regions that would forever remain in freezing cold. The horses had now entered unfamiliar terrain. An enormous scorpion vexed by this unwonted intrusion flicked its immense tail at the galloping horses. The horses in a panic plunged too close to the earth, burning parts of it that turned into great deserts. Neighing hideously, the horses bolted up again, this time to be singed by an angry dragon that spewed flame and smoke at them. The horses and the chariot flew totally out of control as Phaethon cried in despair, terrified and helpless as he was.

Zeus, King of Gods, who had been watching with consternation the disastrous venture of the hapless youth, decided to put an end to the trail of destruction and hurled a thunderbolt at Phaethon. Phaethon was killed instantly and his lifeless, smouldering body dropped from the great height into the river Eridanus below and sank slowly to the bottom. Phaethon's sisters, who had followed their brother's ill-fated adventure, sat by the river and wept in silent sorrow. The grieving maidens were turned into poplar trees. And their tears were metamorphosed into beads of amber. The horses, spent and subdued, returned to the stables of Helios.

Phaethon had a dear and tender companion, Cycnus, King of the Ligurians, a youth of rare beauty and an accomplished musician. He was heartbroken on learning about Phaethon's fate and wondered whether his beloved friend could yet be rescued if he were still alive. Cycnus plunged into the river Eridanus in his search for Phaethon and swam around the gushing water, diving again and again, looking for at least the body of his companion. His beauty and graceful movements made Cycnus resemble a swan swimming in the waters of the river. His lamentations for his lost friend sounded like sad sweet music, a dirge sung to his own death as he perished in grief. This music of boundless pathos came to be known as the Swan Song. The gods, profoundly moved by the tragic end of Cycnus, raised him to the heavens and placed him among the stars. He lives on in radiant immortality as the constellation Cygnus, the Swan, his outline marked by sparkling stars.

Long ago, in the neck of Cygnus the Swan, a star was born from vast clouds of gas, and shone for eons, only to be quenched out in cold finality as happens to all stars in one way or another. This star now adorns the neck of the Swan like a black pearl set in an aura of resplendence.

And it is said that in the still of the night one may be able to hear, wafting from the direction of the constellation Cygnus like a whispered melody carried by the wind, the sad strains of the Celestial Swan Song.

Chapter 18

CIBO PER LA MENTE

'What do you mean: "... whether black holes are part of physical reality", Mike?' asked George, leaning forward and looking intently at Mike Brown, our astronomer friend. 'Is this an existential, ontological, metaphysical question or what?'

'A purely astrophysical question, George,' replied Mike, his ready boyish smile lighting up his face.

We were seated around two tables placed together at Bruno's – Mike, George, George's three students, and, of course, myself.

'What I mean is this,' continued Mike. 'As viewed by a distant observer, namely us, the collapse of a star into a black hole takes infinite time. In other words, you don't see the black hole forming at all. So how can you say it exists as part of physical reality?'

'But you know very well that the star collapses in a finite proper time. Therefore the black hole is part of reality.'

'An unfortunate astronaut sitting on the star's surface may observe this collapse in a finite time of his, but I don't,' countered Mike. 'So the black hole may be the astronaut's short-lived reality, but not mine. I am an observational astronomer and I want to observe the event horizon. Not just go by the theory.'

'Do you know what Einstein told Heisenberg? *It is the theory that decides what we can observe*. So there!'

'Allow me to quote Einstein from his *Autobiographical Notes*,' I joined in the debate. 'He wrote: *Physics is an attempt conceptually to grasp reality as it is thought independently of its being observed. In this sense one speaks of "physical reality"*. That supports George.'

'You guys keep quoting Einstein like the Devil quoting the Scriptures,' protested Mike his grin widening. 'You know what the great Galileo said: *In questions of science the authority of a thousand is not worth the humble reasoning of a single individual.*'

‘Mike is right, George,’ I added. ‘And Leonardo da Vinci said: *Whoever in discussion adduces authority uses not intellect but memory.*’

‘Come on, Alfie, you cannot quote on both sides of the argument,’ protested George.

‘I can, George, because I am neutral!’ I asserted.

‘Watch out, Alfie,’ warned Mike laughing. ‘You have read Dante’s *Inferno*. Don’t forget he tells us that the hottest corner in hell is reserved for those who remain neutral in a conflict!’

The three students were enjoying themselves thoroughly listening to this exchange.

‘There is an irony here,’ commented Sunny. ‘Our mentors are calling on authorities to prove one should not appeal to authority!’

‘Yes, for once Sunny is right,’ added Wei-Li. ‘Irony has negated all their arguments.’

Paul, ever the voice of reason, spoke up, smiling and shaking his head.

‘Is this some kind of war of words or battle of quotations? I thought we were talking about black holes. If I remember right, Mike was demanding evidence for the existence of the event horizon.’

‘I know fully well what Mike wants me to say, Paul,’ remarked George. ‘He wants to play the devil’s advocate. Why should I give him satisfaction? He knows fully well the answers to his own questions.’

Mike’s grin widened even more.

‘All right, let me concede gracefully,’ said Mike. ‘The crucial question is whether we are dealing with a material surface, such as that of a neutron star, or the all-absorbing sink that the event horizon is. The difference shows up in observations all right.’

‘Ah, now the man is talking,’ commented George. ‘Tell us the latest, Mike.’

‘I don’t know about what is latest, George. Things keep changing so fast nowadays,’ said Mike. ‘Anyway, let me tell you about some interesting observations. You know that almost all galaxies harbour supermassive black holes at their centres. Now, there is this galaxy labelled by astronomers as MCG-6-30-15.’

‘Sorry to interrupt you, Mike,’ I said. ‘What does that label stand for?’

‘All right, if you want to know,’ answered Mike. ‘The letters MCG stand for Morphological Catalogue of Galaxies. It is based on the Palomar Sky Survey Atlas. And the numbers indicate the location of a particular galaxy. So, this galaxy has an active nucleus. In other words, at its centre lurks a massive black hole endowed with an accretion disk. Astronomers have very carefully studied the radiation coming from the disk. They have observed characteristic emission lines due to ionized elements. These elements are in a stable orbit around the black hole. And the radiation they emit exhibits high gravitational redshift. From this redshift one can easily estimate the radius of the orbit. And it turns out to be only about twice the gravitational radius.'

'That is fantastic, Mike,' exclaimed George. 'So, these astronomers have pinned down a spinning Kerr black hole after all. What do you know!'

The students nodded in agreement. They too seemed to be quite impressed.

'What is going on here, George?' I asked. I didn't know what was happening.

'You explain, Mike' said George.

'All right, George must have told you about orbits around black holes, hasn't he, Alfie?' asked Mike.

'Yes, he has,' I said.

'In the case of a Schwarzschild black hole, the event horizon has a radius equal to the gravitational radius, right? And the stable orbits start from thrice the gravitational radius. But in the present case, astronomers have found a stable orbit at around twice the gravitational radius. This indicates that the black hole is the spinning Kerr type, since only in that case can one have stable orbits at less than thrice the gravitational radius.'

'Ah, now I understand why you guys are so excited,' I remarked.

'That is not the end of the story,' continued Mike. 'By careful analysis of the spectrum, the observers have calculated the innermost stable orbit for the Kerr black hole on hand. And they have come to the conclusion that this orbit could be as close to the black hole as slightly more than half the gravitational radius.'

'This is really something, Mike,' remarked George. 'Alfie, just now Mike reminded us that the gravitational radius is the same as the radius of the Schwarzschild black hole. So if the innermost stable orbit has a radius that is only half the gravitational radius, then we could not be dealing with a Schwarzschild black hole at all. The orbit would be well within the black hole, which is impossible. On the other hand, such orbits are possible in the Kerr spacetime. Here we can go even further and say the black hole is almost extremal, spinning with nearly the maximum angular momentum. In that case, stable orbits can exist starting from just outside the event horizon. And radiation must be coming from one of those orbits close to the black hole. I wouldn't be surprised if the astronomers actually determine the angular momentum of the black hole one of these days.'

'You know, listening to all this I get a funny feeling,' I said hesitantly.

'Funny feeling! What funny feeling?' George raised his eyebrows.

'It is like this,' I explained. 'I know that in theory you can do exact calculations and so you can talk about things like orbits, their dependence on the mass and the spin of the black hole, and so on in a precise manner. But how about observations? How exact are they? After all, you are not conducting controlled experiments in the laboratory. You are looking at objects so far away, and that too without any control over them.'

'Did you hear that, Mike?' George turned to Mike with a smile. 'What have you got to say to Alfie's query?'

'You have an excellent point there, Alfie,' nodded Mike appreciatively. 'Astronomical observations can be quite difficult and often tricky. They have to be confirmed by repeated observations and preferably by different techniques. The observations we are talking about in regard to black holes seem to be sound. Hopefully they will be confirmed beyond doubt.'

'Let us say then that astronomers have pinned down a spinning black hole. Maybe they will observe all the effects of rotation George has been talking about,' I said. 'All right, you guys have been telling me that there is an immense black hole at the centre of almost every galaxy. What kind of process gave birth to this extraordinary offspring?

'There are two possibilities here, Alfie,' answered Mike. 'The first, a regular stellar black hole, say of ten solar masses, formed to begin with at the galactic centre by gravitational collapse. As you know, we have a perfectly reasonable mechanism for this by the way of stellar evolution. Then this ravenously hungry baby started relentlessly gobbling up the abundant food available in the form of stars and dust around it. Lots of junk food, you know. As a result, it grew and grew, ending up as the obese supermassive black hole we have today.'

'What is the other scenario then?' I enquired.

'Well, the giant was created straight away in the early epochs of the universe, when the cosmic density and pressure were extremely high. In this case, the black hole could have acted as a seed for the formation of the galaxy.'

'Which came first, the galaxy or the black hole? The primordial version of the chicken and egg question,' chuckled George.

'You know what Samuel Butler said about this question?' I quoted, '*A hen is an egg's way of making another egg*.'

'That really is a nice quotation, Alfie,' said Mike. 'But there is no such relation between a black hole and a galaxy.'

'But there is in the case of the universe as a whole,' Sunny said. 'The Big Bang and the Big Crunch are the two eggs, and the universe in the middle is the Big Hen.'

'And God could be the supreme Egg Foo-Yong Maker!' added Wei-Li.

'These two have an incurable eggomania, talking about eggs all the time,' commented Paul. 'In any case, all this is absurd. The universal expansion is accelerating. So there will be no Big Crunch.'

'So much for the hen and the egg,' I concluded. 'What else is new about black holes, Mike?'

'Let me think, we discussed quite a bit about the detection of black holes the other day at the Observatory. Didn't we?' responded Mike. 'Well, we didn't talk about Gamma-Ray Bursts or GRBs as they are called.'

'What are they? Another proof of black hole's existence?' I asked.

'Not exactly, Alfie. But very interesting observations that in all probability involve black holes,' replied Mike. 'Our story begins in the nineteen-sixties. At that time, the United States Air Force started launching the series of Vela satellites. They were supposed to detect nuclear explosions that violated the Test-Ban Treaty.'

'Ah, the spies in the skies,' commented Wei-Li.

'We in the inscrutable East prefer spice to the spies, don't we, Wile-E?' put in Sunny.

'Except for the spy Mata Hari.' Surprisingly, it was Paul who said that. 'Sorry, Mike, these two infect everyone with their insanity. Please go ahead with the GRBs.'

'Well, the satellites failed to detect any tests of nuclear weapons,' continued Mike. 'Nevertheless, they yielded some fantastic results, as the Air Force scientists realized. These satellites had recorded astronomical events that turned out to be the GRBs. Over the years since then, lots of data have been collected. Normally, these bursts last from one second to some hundreds of seconds. More recently, that is in the nineteen-nineties, satellites have observed visible light emitted by the bursts or the afterglows as they are called. Amazingly, these gamma-ray bursts come from as far away as the remotest galaxies in the universe. During their short duration, they outshine their host galaxies. What is more, bursts have been observed whose energy output is comparable to that of the entire universe! Can you imagine that? This means that the energy released is equivalent to a considerable fraction of a solar mass converted entirely into radiation. And another thing. The short durations of the bursts indicate that some compact objects must be involved as the source of energy.'

'How do people explain this phenomenon, Mike?' I asked.

'As I have told you earlier, Alfie, I am only a poor, honest observer. Theorizing is left to people like George.'

'He is an honest observer and I am a cheating theorizer, how do you like that!' chuckled George. 'In any case, these kids have been following the modern developments. They will tell you what might be happening here.'

'Ah, the buck stops with us,' said Sunny. 'Well, nobody is certain as to what is going on. It could be a binary system consisting of two neutron stars that collide and coalesce at high speed. They form a black hole if their total mass exceeds the neutron-star mass limit. In the process there can be a catastrophic explosion giving rise to the gamma-ray burst.'

'An alternative is that the binary is made up of a neutron star and a black hole,' offered Wei-Li. 'The neutron star is shredded by the tidal forces of the black hole, producing a ring of matter. This material spirals into the black hole, ejecting a jet of gas that generates a burst of energy in the form of gamma-rays.'

'There is at least one more mechanism that has been proposed,' added Paul. 'The whole thing is supposed to happen within a very heavy star leading to a super supernova. This explosion has been christened a hypernova. This is accompanied by the formation of a neutron star, which after a short existence collapses to a black hole. The energy released in this process bursts out in the form of gamma-rays.'

'Which one of these mechanisms is operating to generate the gamma-ray bursts?' George asked the rhetorical question. 'No one knows at the moment. Nonetheless, it is only gravitation that can account for the enormous energies that are involved. And where there is energy, there is a black hole.'

'*Video barbum et pallium, philosophum nondum video*,' I said.

'What is this video business, Alfie?' frowned George. 'If it is anything obscene, don't translate it, there are children here, you know.'

'That is what the philosopher Gallius said, George,' I replied. 'It means: *I see the beard and cloak, but I do not yet see the philosopher.* Only circumstantial evidence for the existence of the black hole so far I must say, and no direct observation.'

'But I have directly observed the site of the first man-made black hole,' announced Sunny solemnly, surprising everyone present.

'What do you mean a man-made black hole, Sunny?' queried George.

'I shall reveal what I have seen with my own eyes,' continued Sunny with dignity. 'In the year 1757, Siraj-ud-daula, the Nawab of Bengal, is said to have imprisoned 146 British people in a small room measuring 18 by 14 feet. Apparently, only 23 survived. This came to be known as the Black Hole of Calcutta.

It was the first black hole made by man by compressing a large amount of mass into a small volume. I have visited the site on which this Black Hole stood long ago, if a black hole can manage to stand that is. But I am told that the story does not stand up completely under the scrutiny of historians.'

Wei-Li made circles in the air around his temple to indicate that Sunny was crazy.

'All right, so much for history,' said George. 'Let us get back to the astronomical black holes then.'

'Before we take up astronomical black holes, it looks like we are headed for a short gastronomical break,' I said glancing in the direction of the kitchen.

A waiter came over to our table followed by Bruno, who was coordinating this special dinner. The waiter placed before each of us a small plate of the appetizer and a glass of wine.

'What *is* this, Bruno?' asked George holding up one of the several ornate pieces that made up the appetizer. 'Never seen it before.'

'I know that,' answered Bruno. 'Real special, you know. It is *Fiori di Zucca Fritti*, fried flowers of a rare kind of zucchini. And the wine is Amerone' Bruno withdrew with a satisfied smile.

'I am turning green as salad,' Mike said.

'Why is that?' asked George raising his eyebrows.

'Envy, George, envy!' replied Mike. 'You guys enjoy this kind of feast whenever you want. But look at me, tied to the telescope, a slave to the stars. Doomed inside a dome!'

'Oh, come on Mike, enough of your alliterative agonies,' protested George. 'As if we don't know about the all-night parties you observational astronomers throw.'

We savoured the delicately spiced flowers and sipped the delicious wine in silence for a while.

'All right, back to business, folks,' Mike resumed our discussion. 'Alfie wanted to know how to pin down black holes by direct evidence.'

'This guy is insatiable, Mike' said George pointing at me. 'When we met in the Observatory, we told him that it would be possible to do so through gravitational waves, didn't we?'

'Sure you did, George,' I responded. 'But where do you stand in your struggle for looking the black hole right in the face? What is happening with gravitational wave detection? That is what I want to know.'

'Fair enough,' replied George. 'It is a tremendous job in which theory and experiment have to go hand in hand. First of all, one has to compute the exact details of the gravitational waves emitted by possible sources such as a black-hole binary or, in other words, two black holes going round each other. As I mentioned earlier, these details include the amplitude of the wave, its frequency, shape or the wave pattern, and the energy carried away.'

'One moment, George,' I interrupted George. 'You told me that Einstein himself had predicted the existence of gravitational waves and had even derived the formula for its emission. So, what is there for you theoreticians to derive?'

'Well, Alfie, Einstein derived his equation to the lowest approximation when gravitation can be considered to be weak enough,' explained George. 'First of all, he assumed that the spacetime in which the process occurred was flat. And then, for instance, he did not take into account the radiation reaction.'

'What is that?' I asked.

'You know when the radiation is emitted, it changes the state of the source. This is very important. So, if you apply Einstein's formula to the case of a binary system, you assume that the components are in Newtonian orbits. Compute the energy carried away by the waves. You can then determine the orbits corresponding to the reduced energy of the system. You can carry on this process. This would be quite adequate when the two components of the binary - two neutron stars, a neutron star and a black hole, or two black holes – are far apart and Einstein's approximations hold good. But during the late stages of the binary coalescence when the gravitational fields around them is quite strong, this would be totally inadequate.'

'What do you do then?'

'Well, you start out with the lowest approximation and successively apply modifications due to general relativity. This would mean computing the dynamics of the source, the details of the gravitational waves, and the back reaction of the waves on the source, in a series of iterations. Believe me, Alfie, it is all very complicated. These computations involve analytical derivations often using sophisticated mathematical techniques, numerical methods, and crunching out numbers with the most modern computers. Many groups of general relativists are carrying out this work. That is not all.'

'You have to do more of such complicated calculations?' I asked in surprise.

'You bet, Alfie,' answered George with a smile. 'Suppose your gravitational detector registers some incoming waves. Then you look for the pattern of the waves you have obtained from your calculations. This is known as pattern matching. You prepare computer programmes, or templates as they are called, for all possible sources encoding the respective wave pattern. Using them try to extract the exact pattern of the waves emitted by any source, from the data you have obtained from the detector. Once again, data analysis, including the preparation of the templates, is a highly involved mathematical procedure. Many groups are working at this task too. Oh, well, even to think about all these formidable calculations tires me out.'

George sat back to catch his breath as we waited. In a moment he straightened up. 'I say, this Bruno is amazing!' he exclaimed. 'How does he sense we are changing themes so he can serve?'

George's remark had been elicited by the sight of Bruno emerging from the kitchen accompanied by a waiter carrying food.

'It is your body language, George,' said Mike.

'How do you mean?' George was surprised.

'Mike is right, George,' I put in. 'While we are engaged in discussion, you are animated, leaning forward, and gesticulating constantly. When we are ready to change topics, you sit back relaxed, your hands crossed over your paunch.'

George glanced at his crossed hands and shrugged.

As the waiter served the house speciality, Bruno explained what it was.

'This is really something very unusual you know, *Mozzarella de Buffala*, brought from this small village outside Rome. You see the outer bun-shaped shell is made of a mixture of soft cheeses including the spicy *pecorino*. When you slice it, the milky liquid *mozzarella* inside will flow. Mop it up with a piece of freshly baked bread and eat it with a piece of the outer shell. Heavenly!' Bruno kissed his fingers to indicate the unearthly taste of the dish.

'My God, this is *the* Mozzarella de Buffala!' I exclaimed aloud.

'Don't tell me you have tried it before, Alfie,' remarked George. 'Even Bruno says it is something unusual.'

'No, George, I have never tried it,' I answered. 'But I have read about it.'

As everyone listened intently, I recounted what I had read about the dish placed before us.

While being a guest of the friendly and generous Archbishop Piccolomini just after his trial, Galileo had sent his daughter Suor Maria Celeste egg-shaped lumps of this creamy white *mozzarella* cheese made from water buffalo's milk. While anticipating this rare gift, Maria Celeste had written to him: *Lord Father, I must inform you that I am a blockhead, indeed the biggest one in this part of Italy, because seeing how you wrote of sending me seven 'Buffalo eggs', I believed them truly to be eggs, and planned to fry a huge omelette, convinced that such eggs would be very grand indeed, and in so doing I made merry time for Suor Luisa, who laughed long and hard at my foolishness.*

In her letter Suor Maria Celeste had punned in calling herself a *buffala*, which means both 'blockhead' and 'female buffalo'. One can only imagine how the old Galileo must have laughed at this charming confusion of his daughter.

Bruno listened to me with a knowing smile. Perhaps he was aware of the story and had deliberately brought us this rare gift. We tasted the exquisite cheese dish with not just relish, but with a feeling verging on reverence. After watching our reaction for a moment or two, Bruno nodded and left.

After a while, I came back to where we had left off.

'George, you outlined the calculation part of the gravitational wave detection,' I said. 'But what about the actual detectors?'

'Well, Alfie, last time we spoke of two types of detectors, remember?' began George. 'It all started with the first bar detector Joe Weber built in the nineteen-sixties. More of these bar detectors have been built since then. These bars weigh several tons. A major problem is shielding the detectors from external disturbances you know.'

George paused with a faint smile on his lips. I was sure he was remembering something amusing from the past. I was right.

'Way back, when Joe Weber set up his bar detector, he made sure that he had shielded it from all possible disturbances he could think of,' George told us. 'However, each morning, when he and his students examined the record from the detector, they would find a pronounced peak made around midnight and another similar one a few minutes later. It was too good to have been caused by gravitational waves. So Weber asked one of his students to stay overnight and see why the detector was behaving this way. Well, this student found out that around midnight a security guard came in and banged the door shut. The detector registered a beautiful peak. After going round the lab to make sure everything was all right, he went out banging the door shut again. And there was the second peak. Mystery solved! Of course, Weber removed this spurious gravitational wave effect by talking to the guard.'

I could make out from George's expression the tinge of wistfulness that old memories had brought with them.

'Well, where was I? Yes, the modern-day bar detectors,' continued George as he straightened up. 'In addition to proper shielding, a couple of the bar detectors have been cooled to as low a temperature as a tenth of a Kelvin to minimize the internal thermal vibrations. And, of course, with the steady advance in technology, instrumentation keeps improving. So, one of these days the bar detectors may very well catch some gravitational waves from the sky.'

'How about the detectors based on the principle of the Michelson interferometer you told me about, George?' I asked.

'Ah, that is the second type of detectors I mentioned,' George went on. 'There are several of them around. For instance, there is this Laser Interferometer

Gravitational-wave Observatory, or LIGO for short, in the USA. It is really big you know, with each interferometer arm measuring some four kilometres.'

'Why such a long arm?' I asked. 'Is it like the long arm of the law trying to catch the culprit?'

'Well, gravity waves are too weak to commit any crime, Alfie,' commented George. 'Since the movements of the mirrors would be exceedingly minute, you need long beams of laser light for adequate sensitivity. Building detectors like this requires lot of advanced technology. For instance, you need extraordinarily smooth mirrors and highly efficient lasers that operate continuously. That is not all. The laser beams should be enclosed in vacuum. Can you imagine a four kilometre-long vacuum tube?'

'And, of course, all this needs lots of money too,' added Mike.

'But the pot of gold you get at the end is worth all the trouble you take in creating the rainbow, you know,' remarked George.

'Are there other detectors?' I asked.

'Yes, there are. For instance, a smaller one called GEO600 in Germany and a joint French-Italian venture VIRGO being built near Pisa.'

'Ah, Pisa! That is where the whole game started with Galileo dropping things from the tower,' I said.

'Right you are, Alfie. And they are building detectors in Japan called TAMA and the Australians want to build one too. Who knows, more might come up eventually. And, there is this proposal to launch a detector in outer space.'

'Not spy satellites I hope like the ones that detected the gamma-ray bursts,' I said.

'No, no, Alfie, this one is a genuine gravity wave detector,' said George. 'It is called Laser Interferometer Space Antenna or LISA for short, nice name don't you agree? It will consist of three spacecraft forming an equilateral triangle orbiting the Sun, following the Earth. Each side of the triangle will be some five million kilometres.'

'No special vacuum for the laser beams,' Mike added. 'Outer space does the trick.'

'That is right,' said George. 'The laser light will be transmitted among all the three spacecraft, which means the system acts as two independent interferometers. To build such a detector in space one has to develop new technology. As a matter of fact, so much of physics and engineering has gone into building the earthbound detectors too. And so much has been learnt in the process.'

'So, ultimately the detectors will catch gravity waves that will show directly the existence of black holes. The ultimate goal!' I said.

'That is right,' agreed George. 'Gravitational waves from the black hole in its infinite variety! Black hole forming in asymmetric gravitational collapse. Two black holes in a binary coalescing together. Even two gigantic black holes coming together as two galaxies merge. All these processes emit gravitational waves of different patterns and strengths. But in the end what do we have? As the black hole finds its resting place trembling gently, it sends out its signature coded into waves, its quasi-normal modes. And those, Alfie, one piously hopes to capture. Ah, here comes Bruno with the main course.'

Bruno came over, followed this time by a waiter pushing a cart loaded with plates carrying a variety of dishes. Bruno explained that he had combined together the first course, *primo piatto*, and the second course, *secondo piatto.* The former was, he told us, *risotto alla Trevisana*, a rice preparation typical of Treviso, pink in colour, cooked as it was with tomatoes and herbs. It was accompanied by *totano*, a delicate boneless fish, fried and served with wedges of lemon.

After taking a bite from each of the two dishes, Sunny looked up at Bruno and smiled approvingly.

'*Cibo per la mente!*' Bruno beamed.

'*Cibo da lamento!*' Sunny gave her characteristic, chiming laugh.

'*Sciocchina!*' exclaimed Bruno, smiling broadly, ruffled up Sunny's hair affectionately and left.

'What was all that, Sunny?' asked George intrigued like the rest of us.

'Oh well, Bruno said it was food for the mind,' explained Sunny. 'And I retorted that it was lamentable food. The two expressions sound so similar you know. Bruno called me a little imp in return.'

We ate in silence. How could we dilute the pleasure of having this exquisite meal by engaging in conversation?

As the delicious dishes melted away, Mike spoke up.

'So, George, the detection of gravitational waves is a combination of observational technique and theory. What about the purely theoretical problems associated with black holes? Like information loss for instance?'

'Ah, that *is* an important problem,' George nodded. 'Let us talk briefly about the main issues here. To begin with, we have the star that is destined to collapse into a black hole. It has lots of information contained in its atoms and molecules, all the forces that are operating, various phenomena taking place in its interior and so on. The whole mess.'

'Come on, George, don't you dare call the star a mess,' protested Mike. 'Stars are beautiful and I observe them.'

‘Cool down, Mikey,’ George smiled. ‘All I meant was that the star is a complex system with an enormous amount of information built into it.’

‘Like the letters in a scrabble game neatly arranged into a number of words on the scrabble board,’ said Sunny.

‘Indeed. Now, when the star collapses into the black hole, the black hole swallows up the interior structure of the star in all its variety. Doesn’t it? Only three parameters – its mass, charge, and angular momentum – are left as its characteristics. All the information contained in the star is lost to the black hole.’

‘Washed down the drain,’ commented Mike.

‘Don’t you call the black hole a drain, Mike,’ it was George’s turn to protest. ‘Black holes are beautiful even if I don’t observe them.’

‘So, Sunny’s neatly arranged words fall down the black hole, the letters, the scrabble board, and all,’ commented Wei-Li.

‘Hold it for a moment, let me repeat what I pointed out right in the beginning,’ said Mike. ‘An outside observer never sees the surface of the star cross the event horizon. It is forever visible, however dimly. In effect, the information has not gone down into the black hole at all.’

‘Clever, Mike, clever,’ smiled George. ‘Within the framework of classical physics, what you are saying is perfectly true. You can observe the star forever and therefore the information is not really lost. However, let us take the quantum nature of radiation into account. When the stellar matter crosses the horizon it sends out one last photon. This signals the loss of all information.’

‘Classically, the black hole is formed with an infinitely stretched out whimper,’ I said. ‘And quantum mechanics makes it a sharp, final gasp.’

‘Alfie has a way of expressing things, hasn’t he?’ commented George. ‘So, the quantum has entered the picture. As a matter of fact, we already saw how the quantum sneaked into black hole physics via Hawking radiation, temperature, and entropy. Obviously the quantum is connected to the question of information.’

‘Tell us then what happens to the information,’ said Mike.

‘I can’t tell you what no one knows, Mike,’ replied George. ‘We are in the realm of queries and questions, clues and conjectures here.’

‘Why can’t the information come out along with the Hawking radiation, George?’ I asked.

‘Good question, Alfie. What comes out is thermal radiation, which means it is uncorrelated. You need correlation to carry information. So the Hawking radiation cannot bring us the information that has gone into the black hole.’

'That means Sunny's scrabble letters cannot come out in the form of words,' added Paul.

'What is the end product when the black hole evaporates, anyway?' I queried.

'Again, this is not known for sure, Alfie,' replied George. 'Some physicists think that the black hole just disappears in a burst of radiation. Pop goes the black hole. And the information is irretrievably lost in the process. Some physicists conjecture that the end product is some kind of a nugget, which stores the lost information. But the others object to this saying that it is hard to see how the details of the stellar structure that have been consumed by the black hole can possibly be stored in a nugget, whatever that may be, when the information-free radiation has taken away all the mass. That is not all. Since all equations of general relativity and quantum theory are time-reversal invariant, a few have even imagined a white hole suddenly forming at the moment the black hole pops off. Then all the information gobbled up by the black hole could somehow stream out of the white hole.'

'Do you believe it?' asked Mike.

'Of course not,' George shook his head. 'I don't think any one seriously believes in such a scenario.'

'Then what is the solution to the situation?' I wanted to know.

'Well, Alfie, it is generally agreed that the solution lies in the final theory of quantum gravity,' replied George.

'Which does not exist at the moment,' remarked Mike.

'True, as also the fact that there is Einstein's unfulfilled dream,' said George. 'Einstein struggled for decades to unify gravity with electromagnetism. Now that dream has been amplified. There are three other forces in nature besides gravity, aren't there? Electromagnetic force, the weak interaction, responsible for phenomena like radioactive decay, and the strong nuclear force, all three of which are quantum fields and have been unified. Gravity happens to be the odd man out, resisting quantization and refusing to be united with the other three. Once the theory of quantum gravity has been found, the unification is expected to follow naturally.'

'Ah, the Holy Grail of physics,' I remarked. 'But where do we stand in its quest?'

'Well, Alfie, there are contending theories. Each of them claims to be the right approach to the final version of quantum gravity. For instance, there is the string theory that started off with the idea that all elementary particles are minute vibrating strings. It operates in ten dimensions, the four usual ones and the other invisible extra dimensions. Then again, there is the theory of loop quantum gravity that considers spacetime as something like chain mail made up of loops. These theories have had partial success in describing some quantum effects of gravitation. But they have a long, long way to go before achieving the final goal, if at all they succeed in doing so.'

'George, there must be any number of issues where quantum gravity comes into play. What are they?' I asked.

'Well, Alfie, let me just give some examples in black-hole physics. I don't want to go into the details. Intricacies of quantum gravity may spoil the effect of the wonderful dinner we are having you know,' laughed George. 'Take the case of the singularity at the heart of the black hole. Does quantum gravity avoid its formation? Does it make sure that laws of physics do not break down there? What kind of structure would the region of the singularity have? All these are open questions. Then again, as we have seen, the Hawking radiation raises some important questions. Can quantum gravity give the exact expression for the entropy of the black hole in all possible cases? What about the information-loss problem? That too has to be solved unequivocally by quantum gravity.'

'Tell me, George, are the theoreticians on the right path in achieving their ultimate objective of finding the theory of quantum gravity?' asked Mike.

George paused before answering.

'How can anyone tell, Mike?' remarked George. 'Take the case of conventional quantum theory for instance. There was so much confusion in the case of the radiation emitted by a heated body before Planck gave his law. Energy equated to the frequency with a single universal constant of proportionality thrown in! Could you think of anything simpler than that? And that one equation opened up the entire quantum theory. Could anyone have foreseen all the surprising results that followed? I believe it is the same with quantum gravity. We do not know what the ultimate theory will look like. We do not know what surprises await us.'

'As Goethe's Faust says: *We do not need what we know. We do not know what we need*,' I quoted.

'Well, Alfie, it may be just the other way around,' said George. 'We may need different aspects of all that we know to make up the final theory. And we do know what we need, namely the ultimate theory of quantum gravity. Of course, we may not know the exact pathway to it. A whole new way of looking at nature may be required. For instance, as has been pointed out, it may not be enough if Einstein's theory is modified or a radically new theory of gravitation is discovered. Maybe conventional quantum theory may have to be changed for a happy marriage of the two. After all marriage is an adjustment on both sides, you know.'

There was a momentary lull. Sunny and Wei-Li exchanged glances, stood up abruptly and dashed off into the kitchen.

'These two are plumb crazy you know,' exclaimed Paul. 'I wonder what they are up to now.'

We did not have to wait for long. Sunny and Wei-Li emerged from the kitchen followed by Bruno. Sunny was holding with both hands a large brass plate, a black hemisphere resting on it, while Wei-Li carried a bottle of brandy. Bruno switched off the light above our table, placed a few candles and lit them.

Sunny placed the brass plate carefully on the table and announced in a solemn voice, 'Here is Bruno's unique creation, never made before. It is called *La Torta Buca Nero alla Frutta di Bruno*, a mouthful as a cake ought to be. Bruno's Black Hole Fruit Cake! It is filled with dry fruits soaked in Bruno's special secret sauce. The exterior is made with dark chocolate and blackberry extract which makes it blacker than the black hole.'

'The brass plate represents the accretion disk filled with inflammable fluid that will give off light and heat,' Wei-Li said pouring the brandy generously into the plate. Bruno lit a taper from one of the candles and ignited the liquor which burst into red and blue flames heating up the black hemispherical cake. He then proceeded to slice the cake deftly so as not to break it.

'Watch out, Bruno, the knife may be swallowed up by your black hole,' warned George.

Along with the cake, Bruno served a pale yellow liqueur. '*Limoncello*, tastes excellent with the dry fruits in the cake. Sip slowly, it has strong flavour of lemon, quite alcoholic, could burn your throat.'

'This tastes divine,' exclaimed George tasting a small piece of the cake and sipping the liquor. 'Please, Bruno, join us.'

'No chef tries his own creation when it is perfect, only tastes it while preparing,' smiled Bruno, made a bow and left.

The candle flames flickered and danced shedding pools of light that merged and mingled. The evening had worn on without our noticing the passage of time and was coming to a close.

'It is nearly a century since good old Schwarzschild discovered his solution to Einstein's equations. So simple, so beautiful!' mused George. 'His spacetime harboured this phantom surface no one could understand, a problem child, an ugly duckling. They let it be. It lay dormant for half a century. The sleeping giant!'

‘That is what Napoleon said about my country,’ said Wei-Li. ‘*China, there lies a sleeping giant. Let him sleep, for when he wakes up he shall shake the world.*’

‘That is right, Wei-Li. The Schwarzschild surface shook the world when it woke up all right.’

‘You were there when it happened, weren’t you, George?’ asked Mike.

George fell silent for a long while. His three students, who were hanging on to every word of his, waited in anticipation.

‘As a graduate student, I had wanted to work in either elementary particle physics or general relativity,’ reminisced George. ‘And general relativity won. Gravitation can be a very strong attractive force, you know. My friends said, are you mad? General relativity is dead as a dodo, they said. It had its day, but now those relativity guys just work out the mathematics of the theory. You might as well study Latin grammar they suggested. All that changed, didn’t it? I was lucky you know. To enter the field at the right time, at the right place.’

George continued after a pause. “I remember how John Wheeler was going around talking about the end of stellar evolution with missionary zeal. *Gravitational Collapse: To What?* That used to be the title. Same talk, same title. It is a good idea to give the same title to the same talk.’

‘I agree,’ said Mike. ‘Some people give the same talk under different titles fooling you into listening to what you have heard already.’

‘*Tedious as a twice-told tale, vexing the dull ear of a drowsy man!*’ I quoted Shakespeare.

‘*Gravitational Collapse: To What*? Oppenheimer and Snyder had shown way back how a ball of pressure-free matter collapsed into the Schwarzschild surface, as we called the event horizon or the black hole at the time. A more realistic and detailed picture of the collapse was needed. And deeper understanding of the mysterious surface!’

‘Wasn’t it John Wheeler who coined the term black hole?’ said Mike.

‘Not exactly,’ clarified George. ‘Wheeler himself says that when, in a seminar, he was describing how things fall through this surface, never to come out, someone in the audience exclaimed, why, it is a black hole then! We will never know who it was. But we owe the name to Wheeler who realized how apt it was and popularised it. For all we know, it is that evocative term that enticed so many scientists to work on black holes. And that dramatically changed the course of astrophysics, didn’t it?’

‘Aha, the Schicklgruber Effect,’ I remarked.

‘What is that, Alfie?’ asked George in surprise, while Mike raised his eyebrows mystified. The three students listened with rapt attention.

'Oh, well, scholars have pondered whether the course of history would have been different if Schicklgruber had not changed his name,' I explained. 'But he did change his name to Hitler, which sounded far better than the original one. Could you imagine the Nazis shouting "Heil, Schicklgruber"? He could attract people to his movement only with his new name, some historians think, and that made a lot of difference.' I held up my hand when I saw George was about to speak out. 'I know, George, I know. The name black hole has had a more salutary effect than the one that Schicklgruber adopted.'

'As always, you read my mind well, Alfie,' smiled George. 'Yes, researchers flocked to the black hole. But it took some years, though. In the beginning, there were only a handful of people working on black holes. There was so much scepticism about doing research in the field! If you were working on the stability of the black hole, for example, people asked why anyone in his right mind would like to find out the stability of a thing that could not be detected and might not even exist in the first place. If they came to know that you were studying the scattering of gravitational waves off a black hole, they thought you had gone completely insane looking at the interaction of *two* things, not one, of doubtful existence. You may not believe this. While some laughed, there were some who avoided you as though you were raving mad and would get violent,' George laughed recalling his experience.

'All that changed pretty fast, didn't it?' asked Mike.

'On the theoretical side, yes,' replied George. 'So much emerged out of the black hole – structure and stability, perturbation theory, uniqueness, energy extraction, thermodynamics, evaporation, astrophysical effects, so on and on. Oh, so much beautiful stuff!'

'I know what you are going to say next, George,' smiled Mike. 'It took a long time for the astronomers to accept the reality of black holes. Can you blame them? The whole thing is so strange.'

'You are right, Mike, can't blame them,' admitted George. 'I remember the strange ways in which some of the astronomers expressed their scepticism. When Hawking discovered his radiation and the black hole evaporation, do you know what one of my astronomer friends said? A black hole may not have hair, but it certainly has terminal dandruff!' George laughed for a long time, shaking his head.

'See, we astronomers do have a sense of humour, don't we?' grinned Mike.

'Sure, Mike, but the pendulum swung to the other extreme,' George went on. 'For some time, the black hole was regarded as panacea for all astronomical ills: missing solar neutrinos, missing matter in the universe, missing…'

‘The Missing Link,’ added Wei-Li.

‘Do you know what the term black-hole research stands for?’ Sunny spoke up. ‘It is the area of research into which everything goes and nothing comes out!’

‘Aha, now we know. That is the area of research which you two work in,’ commented Paul.

‘Hey, Paul, don’t say that. It reflects on their advisor,’ said George. ‘Well, things have completely changed now, haven’t they? Black holes have become very much part of reality. Black holes are being detected all over the sky by observations at all wavelengths, optical, radio and X-rays.’

‘But you would like to *see* a black hole through gravitational waves, don’t you, George?’ remarked Mike.

‘Ah, gravitational waves, you have something else there,’ George seemed to brood over past memories. ‘You know, when Joe Weber took the plunge into the detection of gravitational waves, people said he was hitting his head against a stone wall. No chance they said. True, it was a Herculean task. Joe used to repeat the old saying: only dead fish float down the stream, live ones swim against the current. It was a dream all right. I remember Wheeler talking about gravitational waves at that time during a relativity meeting. He had been trying hard to express how he felt about this business, he said. Then he had found a statement when he broke open a fortune cookie after dinner in a Chinese restaurant, which reflected his own feeling. It read: *If it came true, it wasn’t much of a dream, was it?*’

George fell silent.

‘Even that is changing,’ commented Mike.

‘Yes, indeed,’ agreed George. ‘Hope it wasn’t so much of a dream that it won’t come true. I would like to see those waves detected in my own lifetime.’

George paused before going on. ‘How wonderful it would be if some kid were to come over some day and showed me the record of two black holes waltzing around each other and chirping away as they merged. And finally sending off the news that they had coalesced, through some quasi-normal modes, a large peak followed by a few small ones like a mama hen leading its chicks!’

‘Sure you will see them, George,’ said Mike quietly in a calm, assured voice.

A long hush followed. One of the candles had gone out, and the others were about to flicker out too. A feeling of completion seemed to have settled down. Whatever was on our minds had been expressed. George sighed deeply and stood up slowly and so did we. Bruno came over.

‘Bruno…’ began George, but Bruno waved away his thanks.

‘See you soon, Bruno,’ said George. Bruno nodded and shook hands with each one of us. He then kissed Sunny gently on the cheek and Sunny gave him a big hug in return.

We walked in silence until we came to the fork in the cobbled pathway where we had to go our separate ways.

‘Well, Alfie, we have to go to the university,’ said George. ‘Mike and I have to pick up our cars and the kids have to cut across the campus and go home. But we will get together soon. Black holes were just the beginning, the whole universe is waiting for us.’

“See you soon, Alfie,’ said Mike. ‘After all, I haven’t told you what I do for a living, have I? Take care now.’

The three students gave me broad smiles and waved. The group left on their way to the campus. I watched them for a long time, George and Mike leading the way, absorbed in their discussion, followed by the three students, whose laughter lingered on in the air.

Chapter 19

CURTAIN CALL

After returning home, I sat staring out of my window, gazing at the night sky, turning over and over in my mind all that I had learnt in the past few weeks. From the early beginnings of astronomy to the most modern developments, there seemed to be an unbroken continuity of thought with subtle changes and tenuous links. No doubt radical departures were there too. But then, you have to have a starting point in the first place, a reference frame, so to speak, from which you can depart from, don't you? No discovery is made in isolation, in an absolute vacuum. All great discoveries seemed to transcend the confines imposed by the past, confines dictated by a specific area of investigation, tending more and more to reveal the world at large, the universe as a whole. Giants like Galileo, Newton, and Einstein formed the pillars of this intricate superstructure of science. Well, enough of this philosophising, I thought to myself. As you may very well imagine, I wanted to relax and get some rest.

There was hardly a spoonful of the bubble-bath mixture left in its pouch. How long could a free sample last after all! I poured it all into the hot water I had drawn and got into the bathtub. As I closed my eyes, I could feel the bubbles forming in great abundance in spite of the small quantity of the mixture I had added to the water. I could feel them whirring, popping, and gathering beneath me in their buoyant effort to lift me up. This is how I had felt when I had had my first strange and beautiful experience in my bathtub. And now it was happening again.

As before, I stood suspended in the vast night sky. But this time, I could see not only the stars, but also the planets majestically coursing in their orbits. Far away, there were hazy patches of light swirling around almost imperceptibly.

And there was the faint sound of music in the background again, very similar to what I had heard before.

All of a sudden, a large cloud of gas engulfed me, its luminous tendrils brushing against my body as it passed me by. As the vapours cleared, I could see a ghostly figure standing erect in front of me, which seemed like an ethereal vision, a vaguely familiar apparition that had been conjured up from my memory.

'Ah, we meet again, *signore*, as promised and prophesied,' smiled the person that had crystallised in front of me. 'The *signore* must be wondering why the illustrious Giovanni Jacopo Casanova has appeared again, recalled from the past. Please allow me to enlighten you. My mission would not have been complete had I failed to escort you to visit two great men who belonged roughly to my own era.' Casanova paused and then exclaimed, 'Ah, what divine, but sad, music we hear! It is my friend Wolfgang's *Requiem*.'

Casanova closed his eyes and listened, waving his long fingers in unison with the music in the background.

'Well, life is short, *signore*, and so is time borrowed from eternity,' sighed Casanova opening his eyes. 'Let us move on, if you will. I need not repeat, but repeat I shall, how disconcerting the quick transfer in space and time can be, especially the passage in time, which we are about to make. As I had mentioned earlier, the historical figures we shall be visiting are predisposed to quote from their own writings, not from ego, but from habit. Their speech, if expressed in a language unfamiliar to you, will be transformed into your own native tongue by the time it reaches your ears. Yes, *signore*, you will hear the written words of the great, which you might have already read, from their own mouths. Prepare yourself then both in body and mind for a journey to the small village of Arcetri in the year 1638 or thereabouts, there to behold and listen to the words of one of the greatest men my country has given birth to. Yes, *signore*, we shall be in the august presence of that hero of heroes, Galileo Galilei.'

We found ourselves in a modestly furnished room decked with the trappings of a rustic household. This is where Galileo had been confined after his trial, practically a prisoner. Seated at the rough-hewn table in the centre was Galileo. His high domed head was cocooned in white - his full beard, and his snowy hair that cascaded down like a leonine mane befitting the visage of an aging, wounded, yet fierce lion. Head bowed, eyes closed, Galileo pressed his clasped hands against his forehead in an attitude of prayer.

‘*Grazie, grazie, Dio*,’ intoned Galileo. ‘I render infinite thanks to you, God, for being so kind as to make me alone the first observer of marvels kept hidden in obscurity for all previous centuries.’

Galileo opened his eyes and stared vacantly into space. ‘Alas, his eyes have lost their power of vision, *signore*,’ whispered Casanova. ‘He has become totally blind.’

With a wistful smile, Galileo reminisced. ‘Yes, I observed many marvels. I found that the Moon is like the face of the Earth itself, which is marked here and there with chains of mountains and with deep valleys in between. And I showed that Venus changed in shape resembling the Moon. O Nicholas Copernicus, what a pleasure it would have been for you to see this part of your system confirmed by so clear an experiment. I observed the highest planet, Saturn, to be triple bodied. In the very face of the Sun, most pure and serene of all, I saw multitudes of spots. Most of all, I discovered four planets never seen from the beginning of the world right up to our day, circling around the planet Jupiter.’

Galileo groped around the top of the table with both hands. I could see two objects resting on the table, a bottle of wine with a half-filled glass next to it, and Galileo’s old telescope that had been dismantled from its stand. Galileo picked up the telescope and caressed it lovingly.

‘Ah, my spy glass, my glazed optic tube,’ he addressed it affectionately. ‘My friend Kepler thought that you were more precious than any sceptre. You revealed so many wonders, so many new phenomena.’

Galileo paused briefly and went on. ‘I hope these new things will turn out to be of admirable service in tuning for me some reed in this great discordant organ of our philosophy – an instrument on which I think I see many organists wearing themselves out trying vainly to get the whole thing into perfect harmony. Vainly, because they leave or rather preserve three or four of the principle reeds in discord, making it impossible for the others to respond in perfect tune.’

Galileo shook his head sadly. ‘But some consequences, which followed from my new discoveries in contradiction to the physical notions commonly held among academic philosophers, stirred up against me no small number of professors – as if I had placed these things in the sky with my own hands in order to upset Nature and overturn the sciences.’ He gave a hollow laugh and remarked, ‘They seemed to forget that the increase of known truths stimulates the investigation, establishment and growth of the arts; not their diminution or destruction.’

Feeling delicately across the surface of the table with the tip of his fingers, Galileo reached for the glass of wine, took a sip and sighed.

'But you, Kepler, you confirmed everything I wrote without rejecting an iota of it. I indeed congratulate myself on having an associate in the study of Truth, who is a friend of Truth. For it is a misery that so few exist who pursue the Truth and do not pervert philosophical reason.'

Galileo hesitated for a long while as though he was afraid to speak up even to himself in spite of his protective solitude.

'I adopted the teaching of Copernicus many years ago,' whispered Galileo. 'And his point of view enabled me to explain many phenomena of nature which certainly remain inexplicable according to the more current hypothesis. For long, I dared not to bring my many arguments into the public light, frightened by the fate of Copernicus himself, our teacher, who, though he acquired immortal fame with some, is yet to an infinite multitude of others – for such is the number of fools – an object of ridicule and derision, *ridendus et explodendum*, laughed at and hissed off the stage!'

Galileo's lips twisted into a sardonic smile. 'Even after my demonstrating Jupiter's moons with my optic tube, none of the philosophers and scholars conceded their existence. Chemonini, teacher of philosophy at Padua refused even to look through my optic tube. So did my dear colleague Libri!'

Galileo's expression turned one of intense glee, almost verging on the malicious, as he recalled his own past reaction to this foolishness. 'Soon after, Libri died and I could not help commenting: Libri did not choose to see my celestial trifles while he was on Earth; perhaps he will do so now *en route* to heaven!'

Galileo exploded with uproarious laughter slapping his thigh, but fell quickly into his pensive mood again.

'Ah, Kepler, most of my colleagues are incapable of identifying either Jupiter or Mars, and hardly even the Moon. What is to be done? Let us laugh at the stupidity of the crowd, my Kepler. Why are you not here? I wish I had more time to laugh with you. How you would shout with laughter, my dearest Kepler, if you were to hear what the chief philosophers of Pisa said against me to the grand duke… But the night has come and I can no longer converse with you.'

Indeed the twilight rays that had been seeping through the window had been extinguished. Outside it was dark now.

'The two men, Galileo and Kepler, never met, but only corresponded with each other,' Casanova informed me in a low voice. 'In all fairness, it must be admitted that Kepler was extraordinarily generous to Galileo. Unfortunately, *signore*, the same can hardly be said of the latter.'

Galileo closed his eyes in weary loneliness. 'I believe that good philosophers fly alone, like eagles, and not in flocks like starlings. It is true that because eagles are rare birds: They are little seen and less heard, while birds that fly like starlings fill the sky with shrieks and cries, and wherever they settle befoul the earth beneath them.' After a pause he added, 'The crowd of fools who know nothing is infinite. Those who know very little of philosophy are numerous. Few indeed are they who really know some part of it, and only One knows all.'

Galileo plunged into deep thought. After a while he spoke again.

'When I turned my optic tube towards the Milky Way, it dissolved into a mass of innumerable stars planted together in clusters. The galaxy is nothing but congeries of innumerable stars grouped together. Upon whatever part the optic tube is diverted, a vast cloud of stars is immediately presented to view, many of them rather large and quite bright while the number of smaller ones is quite beyond calculation.'

'The Milky Way, the first rung in the cosmic ladder as your modern astronomers have discovered,' commented Casanova. 'Listen carefully to the Master, *signore*, perhaps he has a message for the astronomers of your time.'

'Ah, the universe!' exclaimed Galileo with awe. 'To investigate the constituents of the universe is one of the greatest and noblest problems in nature. But has anyone so far proved whether the universe is finite and has a shape, or whether it is infinite and unbounded? O, foolish man, does your imagination first comprehend some magnitude for the universe, which you then judge to be too vast? If it does, do you like imagining that your comprehension extends beyond the Divine Power? Would you like to imagine for yourself things greater than God can accomplish? And if it does not comprehend this, then why do you pass judgment upon things you do not understand?'

Galileo stroked his beard as he continued. 'I am told by some men that the immense space interposed between the planetary orbits and the starry sphere would be useless and vain, being idle and devoid of stars. What does it mean? That we do not see the world bodies inhabiting this space? Then did the four satellites of Jupiter and the companions of Saturn come into the heavens when we began seeing them and not before? Were there not innumerable other fixed stars before man began to see them? The nebulae were once only little white patches; have we not with our optic tube made them become clusters of many bright and beautiful stars? Oh, presumptuous, rash ignorance of mankind!'

Galileo happily picked up his telescope and stroked it again with great care.

'In our time it has pleased God to concede to human ingenuity an invention so wonderful as to have the power of increasing vision four, six, ten, twenty, thirty, and forty times and an infinite number of objects which were invisible, either because of distance or extreme minuteness, have become visible by means of the optic tube. Will the new observations made with this admirable instrument never cease?' That was perhaps a rhetorical question, which Galileo answered himself emphatically after a moment's pause. 'If its progress follows the course of other great inventions, one may hope that in time things will be seen which we cannot even imagine at present.'

Casanova smiled at my immense surprise on hearing those words of Galileo. 'Yes, those are prophetic words that have come true, are they not?'

Galileo's forehead creased with deep furrows as he thought deeply. I could feel the majesty of his voice as he intoned, 'Infinity and indivisibles transcend our finite understanding, the former on account of their magnitude, the latter because of their smallness. Imagine what they are when combined!'

I was stunned. This was beyond me. Was Galileo foreshadowing all modern thought about the very origin of the universe when the minute structure of the elementary particles is invoked in order to explain the immense galaxies that constitute the cosmos? I did not have to look at my companion. I knew he was smiling again.

Galileo wiped his brows with the back of his hand and picked up the glass of wine again. He sipped long and slow, relishing every drop that touched his lips.

'How I loved to tend to my grapevines,' recalled Galileo. 'I remember how one afternoon, while I worked in my garden dressed in an old leather apron, a group of distinguished visitors arrived. Ha, startled they were to see me in the garb of a common gardener. I am ashamed that you see me in this clown's habit, *signori*, I said, I shall go and dress myself as a philosopher.' Galileo burst out laughing and continued. 'They were surprised that I did not hire labourers to work in the garden. No, no, I told them, I should lose the pleasure. If I thought it is as much fun to have things done as it is to do them, I'd be glad to.'

Galileo nodded several times and laughed for a long time. He took another sip of his wine and continued.

'Ah, the little grape and the shining Sun!' exclaimed Galileo. 'The Sun, with all the planets revolving around it, and depending on it, can still ripen a bunch of grapes, or even a single grape, as though it had nothing else to do in this universe. Now that grape would be guilty of pride or envy if it believed or demanded that the action of the Sun's rays should be employed upon itself alone.' After a pause he added, 'As with the little grape and the Sun, so it is with man and Divine Providence.'

Galileo held up the glass of wine towards the window as if he wanted to see its glow. But the world outside was in darkness now as was his own.

'What is wine?' he mused. 'It is light held captive by moisture.' He closed his eyes and sank back into his chair weighed down by infinite sadness.

'No son of Adam had seen further than I since the beginning of the world,' Galileo heaved a deep sigh. 'This universe which I with my astonishing observations and clear demonstrations had enlarged a hundred-, nay, a thousandfold beyond the limits commonly seen by wise men of all centuries past, is now for me so diminished and reduced, it has shrunk to the meagre confines of my body.'

Galileo sat motionless as he brooded over his own condition.

'Bereft of my powers by my great age and even more by my unfortunate blindness and the failure of my memory and other senses, I spend my fruitless days which are so long because of my continuous inactivity and yet so brief compared with all the months and years that have passed; and I am left with no other comfort than the memory of the sweet former friendships. I shall therefore remain silent, and so pass what remains to me of my laborious life, satisfying myself in the pleasure I shall feel from the discoveries of other pilgrim minds.'

Galileo's countenance turned serene and peaceful with his acceptance of his fate combined with the conscious realization of his achievements.

'I must not forget my book *Two New Sciences* which I believe is superior to everything else of mine hitherto published, for it contains results which I consider the most important of all my studies.'

After a moment of absolute stillness, the room reverberated with Galileo's final words.

'There will be opened a gateway and a road to a large and excellent science into which minds more piercing than mine shall penetrate to recesses still deeper.'

Galileo bowed his head, his clasped hands resting against his forehead. '*Grazie, grazie, Dio…*'

The rest of his prayer was said in silence.

'Yes, *signore*, a mind more piercing than Galileo's came into this world the same year Galileo passed on from it. A man that dared to hold the universe in his palm and change the course of philosophy! I was only two years of age when that man who inherited Galileo's mantle left this world. What would I not have given just to gain a glimpse of that superhuman philosopher in flesh and blood! Of course, the *signore* knows all about him and his monumental work,' commented Casanova. 'But coming back to Galileo, the *signore* must be aware of the fact that he was born on the fifteenth day of February in the year fifteen hundred and sixty-four. Three days later, the great artist Michelangelo Buonarroti passed away. Some believe that Michelangelo's genius was transformed and transferred to the infant Galileo. A transformation from art to science no less! But Galileo was an artist as well, was he not? How else could he have orchestrated the celestial harmony as he did so magnificently? Yet that is but a metaphor. But the cosmic order has found its true expression in real poetry as in my countryman Dante Alighieri's creation. And the celestial sphere shone brightly in the poetic beauty of the greatest writer your language has produced who was also born in the same year as Galileo. What a coincidence! The time has come for us to call upon that man of letters.'

The rustic room in Arcetri slowly faded into a small but comfortable room with sloping roof supported by heavy beams. I could hear the low sound of a distant din rising up from down below, filtered through the wooden floor.

'It is the attic of a pub, *signore*,' Casanova informed me. 'It is pleasant to relax here and to muse as well as to invoke your Muse, in a manner of speaking. Besides, candles that cost considerable amounts are supplied free by the owner of the pub who has a stake in what is being written here.'

A single candle burnt on a rough wooden table. Strewn upon it was writing material – sheets of paper, several well-sharpened quills, and an inkstand – as well as a tankard of ale. The identity of the person sitting at the table was unmistakable what with his high forehead, sharp moustache, pointed beard, and his Elizabethan costume. He toyed with a quill while gazing out of the window next to him. Light was slowly fading, as the sun was about to set.

'You recognized him readily I observe,' said Casanova his eyes gleaming. 'The Bard himself! Note the time difference between my country and here. It was already dark there, but here the night is about to descend. No, the Bard is not in the process of writing a play. He is collecting his thoughts and composing some of his splendid lines as he contemplates the heavens, lines that will be immortalized in his different plays. Let us listen to his thoughts and imagery as he puts them down on paper. As you know, Dante was totally immersed in the universe of Aristotle and Ptolemy. But Shakespeare stood with one foot in Ptolemy's cosmos and the other in that of Copernicus. Pray bear with me as I provide some commentary, which I think is necessary in order to understand the essence of his imaginings. I take the liberty of undertaking this joyful task, especially since I am capable of reading the poet's mind and foretelling what he desires to encapsulate in his lines, if not the lines themselves.'

Shakespeare lowered his eyes, dipped his quill in the ink and started to write.

'Come, let us listen to him describe the radiant Sun and the golden sunset,' invited Casanova.

The glorious sun,
Stars in his course, plays the alchemist,
Turning, with the splendour of his precious eye,
The meagre cloddy earth to glittering gold

'And now the darkness descends.'

Good things of the day begin to droop and drowse,
Whilst night's black agents to their prey do rouse.

'Ah, the stars appear filling the firmament.'

The skies are painted with unnumber'd sparks
They are all afire and every one doth shine.

'Here is our nearest neighbour, the Moon, with her reflected glory,' announced Casanova.

The moon's an arrant thief,
And her pale fire she snatches from the sun.

'Lovely she is, but how fickle!'

O, swear not by the moon, the inconstant moon
That monthly changes in her circled orb
Lest that thy love prove likewise variable.

'Even humans are influenced by that celestial orb that forever follows the Earth.'

It is the very error of the moon;
She comes more near the earth than she wont,
And makes men mad.

'As you know, *signore*, for ages men have been fascinated by meteors, which look like stars streaking across the sky, or falling towards the Earth, but disappearing before reaching the horizon. Let us hear what the poet has to say about them.'

And meteors fright the fixed stars of heaven,
The pale faced moon looks bloody on the earth…

'For ages too, men have been frightened by the appearance of comets. They are beautiful, are they not? It is but human folly that makes them believe that these heavenly bodies portend death and destruction. But the Bard, who well perceived the beauty of these wandering visitors, had to portray the popular myths to entertain the crowds, after all.'

Hung be the heavens with black! Yield, day, to night!
Comets, importing change of time and states,
Brandish your crystal tresses in the sky,
And with them scourge the bad revolting stars…

When beggars die, there are no comets seen;
The heavens themselves blaze forth the death
of princes.

'As you very well know, the Bard was primarily brought up in the tradition of Aristotle,' commented Casanova. 'The crystal spheres, carrying the planets around the Sun, whispered sweet music into the poet's ears, inspiring some of the loveliest lines ever written to flow from his quill. Listen, listen, *signore*!'

How sweet the moonlight sleeps upon this bank.
Here will we sit, and let the sound of music
Creep in our ears…
There is not the smallest orb which thou behold'st
But in his motion like an angel sings…
Such harmony is in immortal souls,
But whilst muddy vestures of decay
Doth grossly close it in, we cannot hear it.

'Ah, but *signore*, having been born in the same year as Galileo perhaps he was quite aware of the Copernican system of the cosmos as well,' Casanova continued his commentary. 'Perhaps he longed to free himself from the constraining spheres of Aristotle.'

Shakespeare gazed intently at the night without, at the sparkling stars strewn across the black velvet of the sky with no end in sight, and then dipped his quill again in ink and wrote down two lines.

I could be bounded in a nutshell
And count myself a king of infinite space.

I could see a pearly grey suffusing the sky as the eastern horizon glowed in iridescent hues while the stars started to fade.

'The poet has many more things to say about the night and its denizens,' said Casanova. 'But, alas, it is time for another dawn and another day.'

Shakespeare wrote slowly now as though he wished to stretch time with his pen.

An hour before the worshipp'd sun peered forth
The golden window of the east

And added,

Look, love, what envious streaks
Do lace the severing cloud in yonder east:
Night's candles are burnt out, and jocular day
Stands tiptoe on the misty mountain tops.

He set down his quill and regarded for a long while the slowly brightening sky outside. At a distance the hazy outline of a strange, tall building was taking shape. Even I could recognize it from the drawings I had seen. It was the Globe Theatre. A longing, lingering expression came over the poet's face. Reluctantly, he picked up his quill again and penned the words,

Can I go forward when my heart is here?
Turn back, dull earth, and find thy centre out.

Then he placed his quill firmly on the sheaf of paper before him with resignation and waited.

As the scene dissolved, the haunting strains of Mozart's *Requiem* started to play in the background again. Casanova spoke softly.

'Who can turn back the Earth and the hands of the clock, *signore*? I long to stay on, but the time has come for me to depart as well. How may I express my exquisite joy of having spoken to you? I believe that I can accomplish the task best by quoting my great compatriot Galileo: *Really, it is a great pleasure to talk with discriminating and perceptive persons, especially when people are progressing and reasoning from one truth to another.*' He smiled and added, 'Ah, I cannot resist the temptation of quoting the rest of his words: *For my part, I more often encounter heads so thick that when I have repeated a thousand times what you have just seen immediately for yourself, I never manage to get through them.*'

The same serene expression I had seen earlier had come upon Casanova's countenance now.

'I have a strong feeling here, where my foolish heart used to be, that we shall see each other, perhaps at another place, at another time,' he said. 'No, *signore*, I am not going to bid you *addio*, my final farewell. Allow me to just say *arrivederci,* goodbye till we meet again. In the meantime, may peace be with you. '

Casanova made a low bow and gradually melted away as the last notes of Mozart's unfinished work trailed into silence. But the music and the poetry I had heard lingered on as I closed my eyes in contemplation of the universe that unfailingly fused art and science into a harmonious blend.

Was I in a trance? The scene around me seemed to shift and change as if I were a lone actor who refused to leave the stage while preparations were being made for the next act.

'You are absolutely right, *mein lieber Herr*, in what you were thinking a moment ago.' I was startled out of my reverie by a voice I had heard long ago. To my utter amazement, I found myself standing in the foyer of Escher's *Relativity* mansion. In front of me was good old Al, looking at me benevolently with his kind, fluid eyes, his face lit up by his gentle smile.

'Yes, the universe blends art and science together. It is the mysterious that stands at the cradle of true art and true science. And science and art tend to coalesce in aesthetics, plasticity, and form. Don't they?' said Al. And he added, 'The greatest scientists are artists as well.'

'A matter of imagination, you know. Imagination is central to both art and science.' It was Bert who had spoken. He had appeared unobserved along with Mr. Stone. 'Oh, yes, imagination is more important than knowledge.'

'I agree with you perfectly,' Mr. Stone concurred. 'I too have come to the conclusion that the gift of imagination means more than the talent for absorbing knowledge.'

A strange feeling came over me. Had I not come across these statements somewhere, sometime, scattered in different places? Sayings of a single person perhaps? I could not recall clearly. Nevertheless, the orchestrated version of those statements as presented by the three now sounded so much more cohesive and meaningful! This characteristic of their combined speech was to continue.

Al seemed to read my mind as he always did. 'Yes, we three keep repeating ourselves, saying what we might have uttered long ago. Perhaps recorded somewhere for all we know. In the past it never occurred to us that every casual remark of ours would be snatched up and recorded. Otherwise we would have crept further into our shells.'

Even the last statement of Al's was uncannily familiar. The three were regarding me with a strange, shared smile.

After a momentary pause, Al continued from where he had left off. 'Take the examples of Galileo and Newton whom you must know quite well, *mein Herr*. Galileo, the father of modern physics – indeed of modern science altogether! Did he not write like a poet? As has been already remarked, did he not transform and transcribe the music of the spheres into his science? And Newton, what can we say about him! In one person he combined the experimenter, the theorist, the mechanic, and, not the least, the master of precise exposition. All these require supreme artistry, do they not?' Al paused before adding, 'In the beginning, if there was such a thing, God created Newton's laws of motion, together with the necessary masses and forces. This is all; everything beyond this follows by deduction.'

'Maybe we should recite the quatrain about Newton we made to illustrate the point. It goes something like this,' said Bert.

Look up to the stars and they will show
How to pay the Master reverence
Obeying Newton's laws they go
Each in its course in eternal silence

'Well, that was only a free translation, you know,' commented Mr. Stone. It sounds so much better in its original German with proper rhyme and rhythm,'

Seht die Sterne, die da lehren
Wie man soll den Meister ehren
Jeder folgt nach Newtons plan
Ewig schweigend seiner Bahn.

'But we cannot stop with Newton, can we?' remarked Bert and Mr. Stone together. Somehow I got the feeling that all the three of them could read the mind of one another. Or should I say they seemed to possess a shared common mind?

'I know, I know,' responded Al to the comment of the other two. 'The concepts Newton created are even still today a part of our thinking in physics, aren't they? But we know that they will have to be superseded if we are to strive for a more profound understanding of nature.'

'Like modifying motion with special relativity,' Bert remarked.

'Like turning gravitation into spacetime curvature,' added Mr. Stone.

'Well, it is all so simple,' said Bert. 'In fact, all physical theories ought to lend themselves to so simple a description that even a child could understand them.'

'Yes, relativity of time is quite simple you know,' Al smiled broadly. 'An hour sitting with a pretty girl on a park bench passes like a minute, but a minute listening to an old professor seems like an hour!'

Al shook with boisterous, booming laughter and the other two joined in.

'But we must remember one thing,' said Bert sobering up. 'Everything should be made as simple as possible, but not simpler. I never understood why the theory of relativity should have met with such a lively reception among the public.'

'I didn't understand it either. Every waiter and every coachman started arguing whether or not relativity theory was correct,' laughed Mr. Stone and added. 'But, you very well know that special relativity was child's play compared to the general theory.' Bert frowned at Mr. Stone in feigned annoyance at this statement that seemed to belittle the special theory of relativity, which was obviously close to Bert's heart.

'Well, if God had been satisfied with inertial systems, He would not have created gravitation, you know!' exclaimed Mr. Stone rolling his eyes heavenwards. 'Ah, the new theory of gravitation! Nature was showing only the tail of a lion. Obviously the lion belonged to the tail. But, because of its large size, the lion could not reveal itself all at once.'

Al chipped in with a sedate smile. ‘In the end, it was nothing but geometry. You must admit one thing. Framing physical laws without geometry is like describing our thoughts without words.’

‘I agree with all this,’ Bert said evenly. ‘But, there are other things too. For instance, we cannot forget the quantum, can we?’

‘Oh, the quantum,’ Mr. Stone shook his head as if in desperation. ‘The more success the quantum theory has, the sillier it looks! Well, let me admit it, quantum mechanics is quite useful.’

‘The theory yields much, I agree. But does it bring us any close to the Old Man’s secrets?’ commented Al. ‘It is hard to sneak a look at God’s cards, you know.’

‘Well, I don’t know. Ultimately gravitation may have to be combined with quantum theory I suppose,’ mused Bert. ‘Moreover, one has to find a common description of both gravitation and electromagnetism.’

‘Oh, yes, the two must be combined. I believe that this is the God-given generalization of general relativity theory. But the equations! Unfortunately, the Devil comes into play, since one cannot solve the new equations,’ Al put in.

‘Alas, the unified field theory has been put into retirement,’ Al continued sadly after a pause. ‘It will be forgotten and must later be rediscovered. This state of affairs may last many more years. I wonder whether physicists have the understanding of logical-philosophical arguments required for the task.’

All three men fell silent absorbed in deep thought. What did Galileo say? Minds more piercing than his would penetrate to recesses still deeper! That hope was fulfilled soon enough in his case. But how long would it be before keener minds, or at least prepared minds, would realize the unfulfilled dream of unification? The state of affairs has already lasted many years. But surely there must be physicists with adequate logical-philosophical insight.

‘Oh, well, sooner or later, others will come along. There is nothing to worry about,’ shrugged Bert, answering my unspoken question.

‘I never worry about the future, it comes soon enough,’ laughed Mr. Stone lightly. ‘Ah, but to be young! Truly novel ideas emerge only in one’s youth, you know,’ said Bert.

‘Later on one becomes more experienced, famous,’ added Mr. Stone.

‘And foolish!’ concluded Al.

The three men roared with laughter together.

The three men looked at one another and announced together, ‘Well, the time has come for our own unification.’

Then an unearthly transformation began to take place. Bert appeared to grow older. He started looking increasingly like Mr. Stone at first and then gradually began to assume the appearance of Al. In the same manner, Mr. Stone too seemed to age and resemble Al more and more. Finally all the three of them stood together looking indistinguishably the same. They smiled at my astonishment.

'That was a transformation in time!' said Bert. 'As you know very well, sir, time is a persistent illusion,'

'So is aging,' added Al.

'We must admit that we are one and the same really,' said Bert and Mr. Stone together. 'Here, let us recite a couplet we made up for you.'

Al, Bert, and Stone
Are all but only one.

'Oh, it sounds so much better in its original German, you know,' remarked Al and now all the three recited together:

Al, Bert, und Stein
Sind alles nur Ein.

At the end of this very brief recitation, Bert and Mr. Stone slowly merged into Al, as two clouds dissolve into another. Al, or should I say the unified personification of the three, stood there looking at me with his characteristic kind smile, his snow-white hair making a halo around his face, a face covered with deep furrowed lines, lines that had been etched by profound thought, lines etched by anguish, and, most of all, lines etched by joyous laughter.

'Well, *mein lieber, lieber Herr*, the time has come for me to take leave of you,' said Al gently. '*Nein, nein*, we shall not say goodbye, for we shall definitely meet again, no doubt about that. Just *Auf Wiedersehen* will do. See you soon, my friend, and peace be with you.'

With that, Al stretched out his arms first in what looked like a gesture of benediction and then as though he desired to embrace the entire humanity and perhaps the entire universe itself. He stood there for the briefest moment suspended in time and then he gradually dissolved away leaving behind vast, empty space.

The bathwater was still warm and the bubbles had moved all along the periphery of the bathtub, hitting and rubbing it incessantly. Under their impact, the bathtub began to vibrate, first imperceptibly and then with increasing resonance, until, finally, I heard the old, familiar, unearthly voice.

'Well, boss, we are together again all by ourselves, aren't we?' rumbled the bathtub. 'Feeling pensive, are we? Like closing a book after having read the last line, tucking away all the characters between the covers? No, boss, the story is far from finished. We have only just read the opening chapter, that is all. We shall go on with it, and all the characters will come back. But, for now, you have had plenty of excitement. You need some rest. Good night, boss, good night.'

As the voice trailed off and the vibrations died down, the bubbles suddenly swarmed all over me, moving around, dancing, whirling, and caressing, and finally they too dissolved into the water.

And I drifted into a deep, dreamless slumber.

Chapter 20

FOUNDATIONS OF FACT AND FANTASY

Often, written words form the foundation stones and the building blocks of all information and knowledge, imagination and fantasy. Don't you agree? No doubt I learnt a great deal of black-hole physics from my discussions with George, Mike, and George's three graduate students. But somewhere along the line, even they would have gathered their information and knowledge to a considerable extent from their study of books, articles, and original papers. Well, I too have benefited greatly from my own reading of several books and articles. What I learnt from discussions and from books not only added to my understanding of black holes and related topics, but also stimulated my imagination and, let me admit it, what may pass for my fantasies. I have listed below some of the books and essays I have come across. I have classified them broadly according to their subject matter. Let me also make a few comments about what I have read.

First of all, I found the books of general interest highly rewarding. I have tried to share some of it with you. The dialogue between Kepler and Tycho Brahe in Chapter 3 as also Galileo's monologue in Chapter 19 are based on original writings and letters, suitably transformed so as to fit into the context. The stalwarts in those days wrote so well! I have listed several books pertaining to the life and work of Isaac Newton. I have always liked the slim volume by Andrade, which is quite nice and charming. But, there is nothing like learning from the Master himself. Of course, it is almost impossible to go through the mathematical aspects of the *Principia*. Nonetheless, Newton's *Scholiums* and general observations and reflections are quite readable and highly interesting. So are the historical and explanatory notes by Florian Cajori that can be found in the edition I have mentioned.

There are many publications containing stories of Sherlock Holmes. But one has to read the writings of scholars specializing in the Holmes-lore, such as those of William S. Baring-Gould for instance, to learn about, among other things, Holmes's scientific experiments and his arch enemy Moriarty's anticipation of modern day developments like relativity and space travel! Holmes's sayings quoted in Chapter 15 have been taken from the following stories: *A Scandal in Bohemia*, *The Boscombe Valley Mystery*, *The Sign of the Four*, *The Adventure of the Beryl Coronet*, *The Adventure of the Empty House*, *The Final Problem*, and *The Adventure of the Abbey Grange.* As with Sherlock Holmes, one can find a number of published versions of *Alice in Wonderland* and *Through the Looking Glass.* I have given reference to the original publication. In the same chapter, I have used quotations from Dante's *Inferno*. Among the different translations of the work, I find the one by Dorothy L. Sayers elegant and powerful. Lines quoted in Chapter 15 come from the following Cantos: *Cantos I*, *III*, *IV*, *V*, *VII*, *XV*, *XXXII*, and *XXXIV*. Again, Shakespeare's works can be found in any number of published volumes. His beautiful astronomical descriptions appearing in Chapter 19 have been taken from the following plays: *Julius Caesar*, *Romeo and Juliet*, *Richard II*, *Henry VI*, *Merchant of Venice*, and *Hamlet.*

Coming to Einstein, there have been an enormous number of books about him. However, I find the two old biographies by Banesh Hoffmann and Ronald Clark still most appealing. John Stachel's writings dealing with Einstein, relativity and other subjects are outstanding in their erudition and meticulous research. As with Newton, or perhaps even more so, it is a wonderful experience to learn from the Master himself. In this regard, Einstein's collection of quotations edited by Alice Calaprice is most rewarding. Here and there, some of Einstein's quotations appear directly. Part of the tub talk of Chapter 10, and the concerted observations made by Al, Bert, and Mr. Stone in Chapter 19 are based on Einstein's sayings with suitable modifications without compromising their authenticity or significance.

Let me say a few words about the general theory of relativity and black holes. Whatever George told me must have come basically from his own research supported by his study of original papers. However, as I have mentioned in my narration, I came across several books on these topics in George's office. I have noted down two books written a decade or so ago specifically about black holes as also an extensively used textbook of general relativity. George recommended to me two modern books on gravitation, which include considerable amount of discussion of black holes. The one by Bernard Schutz contains a lot of information and very little mathematics. The other by James Hartle is an excellent textbook aimed at graduate students. Well, it is my hope that someday, with some effort, I should be able to work through that book in detail. George asked me to take a look at Roger Penrose's work, and that I have included. Reading between the equations, I could get the flavour of Penrose's keen observations and seminal ideas pertaining to advanced topics like black-hole evaporation, information loss, and quantum gravity. George also told me that he liked the volume edited by Bala R. Iyer and Biplab Bhawal very much indeed. It comprises a number of interesting articles by George's contemporaries and younger researchers. These articles discuss the present status and the future prospects of frontier areas of research in the field of gravitation in a comprehensive manner.

One last word. The anecdote, in Chapter 10, of Peter Bergmann helping Einstein do the dishes, as well as those related to Joseph Weber and John Wheeler in Chapter 18, come from the reminiscences of those three scientists as recalled by George.

Let me stop here. I am sure you have your own list of books that you have read and enjoyed. It is my ardent hope that you have now found more titles to add to that list.

I am so happy that you joined me on this passage through space and time. As many wished me during the journey, farewell for now and may peace be with you. Till our worldlines meet again then!

LIST OF SOME SELECTED BOOKS

HISTORY OF ASTRONOMY, COPERNICUS, TYCHO BRAHE, KEPLER, GALILEO

1. Dava Sobel, *Galileo's Daughter*, Fourth Estate, London (1999)
2. Rocky Kolb, *Blind Watchers of the Sky*, Oxford University Press, Oxford (1999)
3. Arthur Beer and K. A Strand (eds), 'Copernicus Yesterday and Today', *Vistas in Astronomy* Vol. 17, Pergamon Press, Oxford (1975)
4. Arthur Beer and Peter Beer (eds), 'Kepler – Four Hundred Years', *Vistas in Astronomy* Vol. 18, Pergamon Press, Oxford (1975)
   In particular: Owen Gingerich., 'Kepler's Place in Astronomy'
5. Peter Machamer (ed.), *The Cambridge Companion to Galileo*, Cambridge University Press, Cambridge (1998)
6. Galileo Galilei, *Dialogues Concerning Two New Sciences*, Prometheus Books, New York, NY (1991)
7. Oliver Lodge, *Pioneers of Science*, Dover Publications, New York, NY (1960)
8. Patrick Moore, *The Great Astronomical Revolution*, Albion Publishing, Chichester (1994)
9. Galileo Galilei, *Dialogue Concerning two Systems of the World: Ptolemaic and Copernican*, trans. Stillman Drake, University of California Press, Berkeley, CA (1967)
10. Arthur Koestler, *The Sleepwalkers*, Pelican Books, London (1982)
11. S.K. Biswas, D.C.V. Mallik, and C.V. Vishveshwara (eds), *Cosmic Perspectives*, Cambridge University Press, Cambridge (1989)
    In particular: Joseph Needham, 'Astronomy in Ancient and Medieval China'
    C.V. Vihsveshwara, 'Geometry and the Universe'
12. Thomas S. Kuhn, *The Copernican Revolution*, Harvard University Press, Cambridge, MA (1979)
13. David H. Clark and Richard F. Stephenson, *The Historical Supernovae*, Pergamon Press, Oxford (1977)

NEWTON

1. Isaac Newton, *Philosophiae Naturalis Principia Mathematica. The Principia: Sir Isaac Newton's Mathematical Principles of Natural Philosophy and His System of the World*, Translated into English by Andrew Mott in 1729. Revised and supplied with a historical and explanatory appendix by Florian Cajori, University of California Press, Berkeley, CA (1946)
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3. William Stukeley, *Memoirs of Sir Isaac Newton's Life*, Taylor and Francis, London (1936)
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5. Richard S. Westfall, *The Life of Isaac Newton*, Cambridge University Press, Cambridge (1993)
6. Richard S. Westfall, *Never at Rest*, Cambridge University Press, Cambridge (1980)
7. Derek Gjertsen, *The Newton Handbook*, Routledge & Kegan Paul, London and New York (1986)
8. Frank E. Manuel, *A Portrait of Isaac Newton*, Harvard University Press, Cambridge, MA (1968)

CONSTELLATIONS AND MYTHS

1. Roy A. Gallant, *The Constellations: How They Came to Be*, Four Winds Press, New York, NY (1979)
2. Robert Graves, *Greek Gods and Heroes*, Dell Publishing Company, New York, NY (1972)
3. *New Larousse Encyclopaedia of Mythology*, Hamlyn, London (1984)

ASTROPHYSICS AND COSMOLOGY

1. Frank H. Shu, *The Physical Universe - An Introduction to Astronomy*, University Science Books, Mill Valley, CA (1982)
2. William J. Kaufmann III, *Universe*, W H Freeman Company, New York (1985)
3. Michael Zeilik, *Astronomy - The Evolving Universe*, Harper & Row, New York (1982}
4. Michael Zeilik and Stephen A. Gregory, *Introductory Astronomy and Astrophysics*, Saunders College Publishing, New York (1998)
5. Herbert Friedman, *The Amazing Universe*, National Geographic Society, Washington D.C. (1975)

EINSTEIN, RELATIVITY, GRAVITATION, AND BLACK HOLES

1. Albert, Einstein, 'Autobiographical Notes' in *Albert Einstein: Philosopher – Scientist*, (ed.) Paul Arthur Schilpp, Tudor Publishing Company, New York, NY (1951)
2. Banesh Hoffmann, *Albert Einstein, creator and rebel*, Viking Press, New York, NY (1972)

3. Ronald W. Clark, *Einstein: The Life and Times*, Avon, New York, NY (1972)
4. Alice Calaprice (Editor), *The New Quotable Einstein*, © 2005 Princeton University Press and the Hebrew University of Jerusalem. Reprinted by Permission of Princeton University Press
5. Stephen Hawking, *A Brief History of Time*, Bantam Books, London (1988)
6. Isaac Newton, *Opticks*, Dover, New York, NY (1952)
7. Leopold Infeld, *Quest*, Chelsea Publishing Company, New York, NY (1980)
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9. Helen Dukas and Banesh Hoffman (eds), *Albert Einstein – The Human Side, new glimpses from his archives*, Princeton University Press, Princeton, NJ (1979)
10. Don Howard and John Stachel (eds), *Einstein and the History of General Relativity*, based on *Proceedings*, 1986 Osgood Hill Conference, North Andover, MA, 8—11 May 1986, Birkhäuser, Boston, MA (1989)
    In particular: Jean Eisenstaedt, 'The Early Interpretation of the Schwarzschild Solution'
11. John Stachel, *Einstein from 'B' to 'Z'*, Birkhäuser, Boston, MA (2002)
12. John Stachel (ed.), *Einstein's Miraculous Year: Five Papers That Changed the Face of Physics*, Princeton University Press, Princeton, NJ (1998)
13. Jean-Pierre Luminet, *Black Holes*, Cambridge University Press, Cambridge (1987)
14. Kip S. Thorne, *Black Holes and Time Warps*, WW Norton (1994)
15. Bala R. Iyer and Biplab Bhawal (eds), *Black Holes, Gravitational Radiation and the Universe*, Kluwer Academic Publishers, Dordrecht (1999)
16. Bernard Schutz, *Gravity: From the Ground Up*, Cambridge University Press, Cambridge (2003)
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19. Gerd Weiberg and Frank Berberich (eds), *Der Einstein–Komplex*, Verlag Das Wunderhorn (2005)
    In particular: Freeman Dyson, 'Every Genius Has a Blind Spot'
    C. V. Vishveshwara, 'Lamentations of Light'
20. S, Chandrasekhar, *Truth and Beauty: Aesthetics and Motivations in Science*, University of Chicago Press, Chicago, IL (1987)
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Panel Discussion, 'Working with Einstein' Panelists: Banesh Hoffmann (Moderator), Valentine Bargmann, Peter G. Bergmann, Ernst G. Strauss

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Bangalore, India *C. V. Vishveshwara*