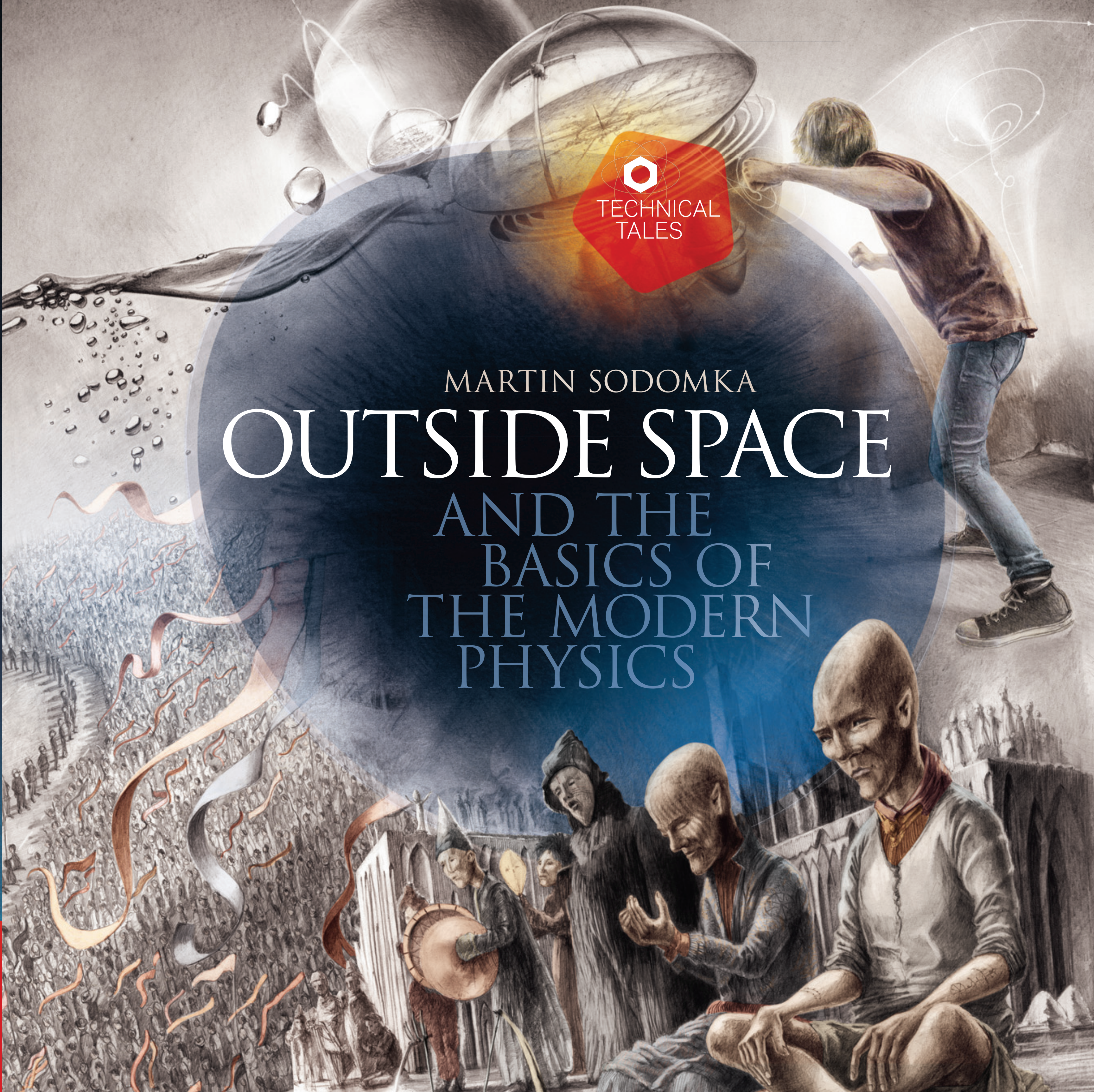
OUTSIDE SPACE AND THE BASICS OF THE MODERN PHYSICS
MARTIN SODOMKA
TECHNICAL TALES



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AND THE BASICS OF THE MODERN PHYSICS

PART ONE: **MATTER**

"Don't tell me that new kid who joined our class today is normal. He must have come straight out of some madhouse if you ask me. What's his name again?"

"Daniel Rubin, and I can't understand why you're being so mean, Ure. You don't look particularly attractive at first sight either!" countered his classmate, a slim girl with a pleasant low-pitched voice.

Ure, a pale skinny boy with a blond mop of hair, muttered something, hoping no one could see his cheeks turning red.

"Adios amigos, got to run," said the third of the group, a dark-eyed boy with a wild afro hairstyle. 'See you in the shed this evening.'

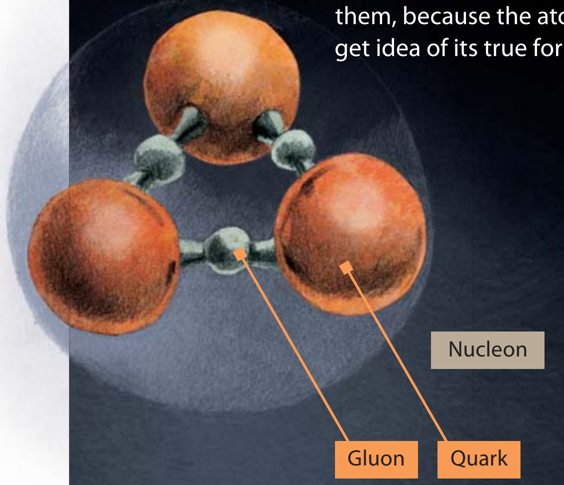
"Kogy! Don't forget to bring the drawing!" Ure shouted after him.

We have thus been introduced to the five main characters in the story that follows. Wait a minute, that's not five! It's true, we've only mentioned four. Don't worry, the fifth character has been patiently waiting on the following pages – for quite some time, in fact. But this story begins several weeks earlier, so let's go back to the very beginning.

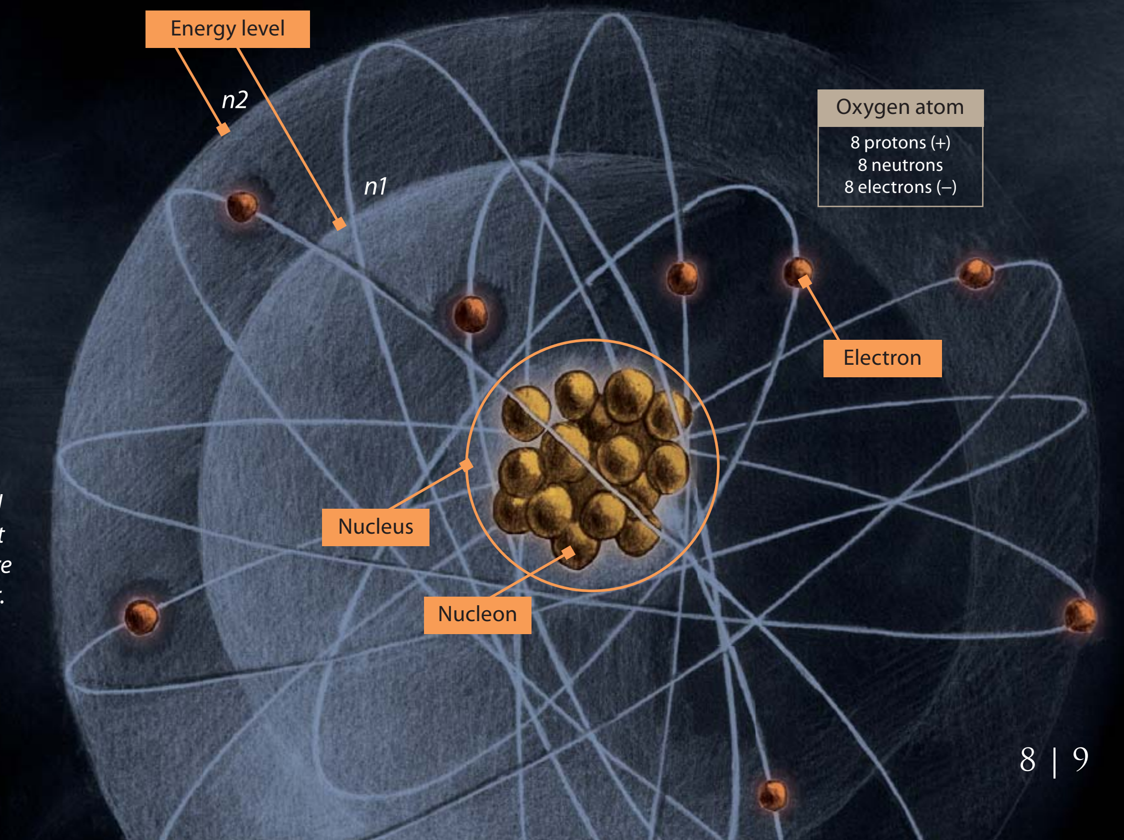
The story told on the white pages may be a mere fantasy, but here on the black pages we will try to write only the truth. Searching for the truth about the world that surrounds us is the ultimate goal of the science of physics. This task is not an easy one – the more questions you answer, the more you are presented with. You also have to keep in mind the fact that it is a goal which may never be attained.

ATOM

Fortunately, physicists are already sure about some things. For example, they know that the material world is made up of atoms. The atom consists of protons and neutrons, which form its nucleus, and electrons, which circle around the nucleus at given energy levels. Both protons and neutrons are composed of smaller particles called quarks. This can be seen in the picture below. But you don't need to look too hard at them, because the atom doesn't look like that in reality. To get idea of its true form it's necessary to know the proper scale. At this point, we can only rely on our imagination, something we're going to do quite often in this book. So, if you imagine that an atom took up a space as big as a sports hall, its nucleus would be as big as a pinhead. It's rather difficult to talk about the size of electrons, but experiments show that they are several orders of magnitude smaller than an atom's nucleus. You may be wondering why we're focusing on these dimensions. Well, it's because it emphasises one very interesting fact, which is that matter is, in fact, one big, sparse, flickering nothingness. Other observations underline this point as well. A neutrino, a particle about the size of an electron, could fly through the Earth without colliding with any other particle. After it has burnt out, a star ten times the size of our Sun may be transformed into a so-called neutron star of just ten kilometres across. If we were able to break off a piece of it, about the size of sugar-cube, this fragment would be as heavy as the highest mountain on our planet, Mount Everest. Perhaps only this substance could rightly be called matter.



The word nucleon is commonly used to refer to both neutron and proton. The nucleon is made up of three quarks. Particles called gluons provide the force that holds nucleons and the entire nucleus of an atom together.



Behind a blackened picket fence stood a little garden house, surrounded by overgrown grass and fruit trees. This poorly tended land was part of a group of allotment gardens situated in a rather unromantic location between a motorway and a railway line. Nevertheless, this strangely situated place had one significant advantage – it was just a short walk from the city centre and allowed the owners of the allotments to enjoy the illusion of country life without the need for long journeys.

The garden house belonged to Kogy's parents. They had divorced several years earlier and the property had passed to his mother, who didn't have the time or the inclination to look after it. Everything was slowly falling into disrepair when Kogy and his friend Ure decided to take it over and make it their clubhouse. Not that the garden would benefit in the slightest. They started calling the poor garden house 'the shed' and didn't lift a finger to keep it properly maintained. Their interests and plans lay elsewhere.

Kogy and Ure had shared a common passion since they were little children - space. They built models of spaceships and devoured not only science fiction books but also publications written by experts in the field. And they could probably identify every constellation in the night sky. Once they had completed their secondary school education, they both decided to apply for a place at the renowned Mathematics and Physics Lyceum known as MATPHYL, and after going through a rigorous admissions procedure, they were both overjoyed to be accepted.

However, once they started attending MATPHYL, their enthusiasm for space and astronautics started to wane a little. At the very beginning, at least, they spent a lot of time studying new subjects. The teachers were very strict and demanding and started right off with differential calculus, relativity theory, and quantum mechanics. Another reason for the dwindling strength of their common interest was the girls around them. For some inexplicable reason, they had suddenly ceased to be annoying beings that a proper boy wouldn't squander his time on. Although Kogy and Ure continued going to the shed, where they thought up designs for a rocket capable of reaching Mars, the theme of their research very often ended up being redirected towards the mysteries of the opposite sex.

In their class, there was a girl named Lucy, who everyone called Hooky. Regardless of the shape of her nose, both boys liked her from the outset. There was a certain spark in her and even though she was pretty, she wasn't just a pretty face. And not only that, she wasn't a fragile flower either. Although many young ladies would probably have been distraught to have been given such a nickname, it was water off a duck's back to Hooky. It may have been the case that Ure and Kogy had no fear of flying into space, but neither of them had yet plucked up the courage to approach a girl like Hooky. Happily for them, chance intervened.

"Would any of you first-year students be interested in tomorrow's evening lecture for older students on rocket engines?" asked the class teacher. "Professor Schmidt of the National Research Agency is coming." Three hands went up, the third of which was Hooky's. After classes had ended, she headed straight for their desks and said "So, you're interested in spacecraft, are you?"

"You could say that," replied Ure.

"We're trying to devise a rocket that can reach Mars and then also manage to get back to Earth," added Kogy. The girl casually looked two boys over and then asked a second question.

"May I see your plans?"

Two days later, right after school, Kogy and Ure took Hooky to the shed to show her the results of the work they had done so far. They walked the way to the allotment gardens in silence. The two otherwise talkative gentlemen were rather shy in front of the girl, and Hooky was not in the habit of talking any old nonsense just because it was quiet. On weekdays the gardens were almost deserted, and the only person there was an older man, hoeing his plant beds half-heartedly. Soon they were there and Kogy was unlocking the shed door. Without commenting on the dishevelled state of the place, Hooky whistled appreciatively as they entered.

"Here's a drawing of the whole configuration. You can see there all three levels of the rocket, and here's the landing module," said Ure, unfolding a large sheet of paper on the table.

"The most difficult part is not getting to Mars," added Kogy, "the problem is getting back to Earth. That's because the spaceship has to haul an enormous amount of fuel for the journey home."

"One option is to manufacture new fuel directly on Mars," said Ure, taking over again, "We've been thinking about this solution a lot over the past few days."

Hooky listened carefully and studied the drawings for a long time. Finally, after a while, she said, "I must say I'm impressed, but can I just say something?"

Ure gave Hooky a look that indicated she should go on.

"Let's say that one day someone is able to build this kind of rocket. It'll take almost forever fly to Mars, and when the crew get there they'll be at the limits of their endurance, completely exhausted by living in that small space for such a long period. But okay, let's say they manage to land it and everything turns out fine, what then? What awaits the poor crew of the ship? A big heap of frozen red rocks, that's what!"

Kogy had a rather quick temper and could often fly into a rage in a matter of seconds. The way Hooky had evaluated their work fired him up at once.

"So you came here just to make fun of us?" he snapped angrily.

"Wait, wait, hold on a minute!" cried out Hooky, clearly shocked by Kogy's outburst. "I told you I liked your designs. My point relates to the purpose of the expedition. You understand what I'm saying – what's the point?"

"What point, what do you mean?" snorted Kogy.

"Okay listen," said Hooky. "In our solar system, there are almost certainly no other advanced creatures. Also, apart from Earth, there aren't any places with suitable conditions for life - unless we count Saturn's moons, where, somewhere below the surface, a few microbes may somehow survive. So, what I'd really like to discover is what proper life in the universe looks like. I'd like to explore completely different worlds, not just take a peek around the corner of the street."

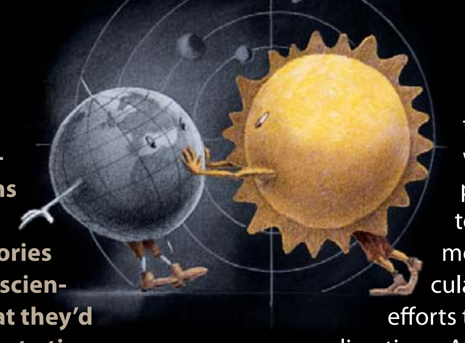
"Nobody is able to make that kind of spacecraft. We don't have the right technology yet," countered Ure.

"And what about your idea of making fuel on Mars?" replied Hooky. "There's no technology for that either. After all, we're only talking about plans and ideas. I don't suppose you intend to go to the DIY store and start building an actual rocket right here in the garden … or do you?" she added in surprise, when nobody responded.

"Of course not," said Ure, waking up, "do we look like idiots?"

"And what about you – do you know what a spaceship that can take people to the stars looks like?" sneered Kogy, sceptically.

"As a matter of fact, I do have one particular idea. And if you let me join you, I'll try to explain what it is."

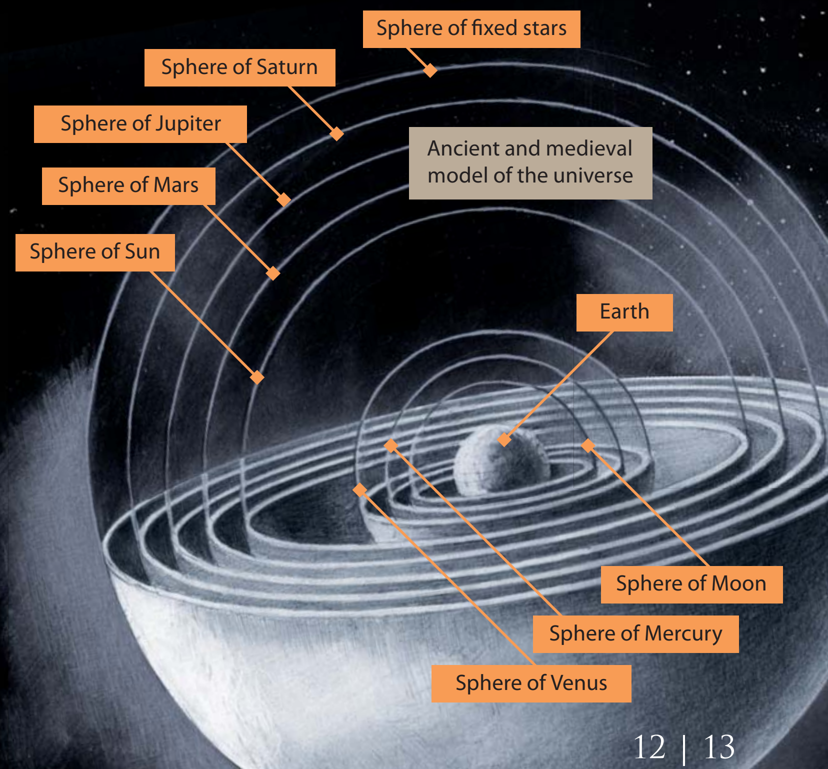


Down the ages, mankind has always longed to understand our world. Today, it may seem that many questions have been answered and there's no reason to doubt the truth of the theories that explain them. But scholars and scientists in the past were also certain that they'd discovered the truth, until, from time to time, a genius came along who changed everyone's minds. Therefore, it would be rather foolhardy to believe that today's theories will stand the test of time.

SEARCHING FOR TRUTH

We will probably never know how ancient peoples imagined the world. But judging by what remains of their sacred sites, they certainly weren't fools and perhaps knew some things that we don't have the slightest inkling of today. The first written references to the cosmos date back to ancient Greece. The prevailing view was that the Earth was round and unmoving, positioned at the centre of the universe, with celestial bodies orbiting around it in spheres, including the Sun and fixed stars. At the end of the Middle Ages, a man called Nicolaus Copernicus came up with the idea that the Sun was the centre of the universe. He didn't publish his revolutionary work until the very end of his life, and it was just as well. In those days, the Catholic Church owned the patent for interpreting the world, and, in most cases, any clever fellow who came along and wanted to change something was politely questioned and then burnt at the stake. Several decades later the founder of modern science, Galileo Galilei, demonstrated the accuracy of the Copernican model, obtaining conclusive proof by means of a telescope – his own invention. In this case, the Church showed its merciful face and didn't have Galileo burnt to death, it only sentenced him to lifelong house arrest.

Later came the brilliant thinker Isaac Newton, who formulated the law of gravity and the three laws of motion. His calculations corresponded exactly to what could clearly be observed. This convinced people that physics as a science could pack up and go home because everything there was to know had already been discovered. Thereafter, physicists began to get bored and so continually observed everything around them in more and more detail, measuring with more and more accuracy. But, as time passed, they began to discover that Newton's calculations were not so exact, and the more they drilled down into it, the less the calculations seemed right. It came to a head with efforts to measure the speed of light from different directions. At that time, it was already known that light could travel at a good clip. Now, it's time to pay close attention. When we're moving away from a light source, the measured speed must logically be slower than when we're moving towards it. That makes sense, doesn't it? Well, actually it isn't true – the speed of light never changes. One young employee of a patent office couldn't get this mystery out of his head. One day, he was in the middle of cooking his dinner when a startling idea occurred to him – the speed of light is always the same and nothing can travel faster. So, he sat down at the table, picked up a pencil, and, within a relatively short period of time, completely changed how people understood the functioning of the universe at that time. And just so you don't forget the gentleman's name, it was Albert Einstein.



On her first visit to the shed Hooky didn't develop her idea of a journey into space any further. She needed to go home and told them that she wanted to get everything properly ready. After various postponements, the second meeting took place a week later. Ure and Kogy had been waiting for her for half an hour and they really weren't expecting much.

When she finally arrived, she apologised and pulled some scribbled-on papers and a bottle of water out of her bag. She took a sip of water and without further ado launched straight into her lecture:

"So, if we want to fly to the stars, we have to take into account the fact that it will take a long time. What's the crew going to do in all that time? They're soon going to get fed up with watching TV serials and playing table tennis, especially in zero gravity. That gives us two options. We can either put the astronauts to sleep, that's to say make them to go into hibernation for several years, as they do in classic sci-fi movies, or create the kind of conditions needed for them to live almost like on Earth."

"You mean like going for walks in the woods and swimming in the lake?" said Ure, making a face.

"Not only that, they could be driving a tractor in the fields and harvesting crops, or going on all-day hiking trips."

"Hold on, I was only kidding, you look like you mean it."

"But it can't be done without one essential thing." said Hooky, continuing with her idea.

"Guess what it is?"

"Giant rocket engines that we can attach to the Earth, so we can fly off with the whole planet?" joked Kogy.

"That's an interesting idea," mused the girl, entirely seriously, "but I was thinking of something else. Travelling such a long way isn't possible without gravity. Gravity, that's what I was thinking of! Astronauts who live in a state of weightlessness for just half a year find it very hard. Their muscles grow weak and they have to work out constantly. And even then, after returning back to Earth they can hardly walk. But the journey to other stars will take years ..."

"I never thought of that," interrupted Ure. "In films, people on spaceships journeying through space just walk around, they don't float.

"That might be because it's difficult for filmmakers to create the illusion of weightlessness, and also the fact that the story would be a bit slow-paced, if the main characters had to flounder around from place to place."

"I've just thought of something," interjected Kogy, excitedly, "what if the spaceship rotated? The centrifugal force would press the astronauts to the floor – that's pretty much like gravity."

"That's not a bad idea," said Hooky.

"It'd probably make you want to throw up though," countered Ure, "your brain knows when you're upside down."

"Even when you're in space and weightless?"

"I don't know, I've never tried it."

"There's no need to get all wound up about it," said Hooky, interrupting the beginning of an argument. "I've already solved the problem."

"How?"

"The ship will continuously accelerate."

"Accelerate? Throughout the whole flight?" asked Kogy, in disbelief.

"That's right, at a rate of 9.8ms^{-2}"*

"There's something familiar about that number."

"There should be, it's gravitational acceleration on the surface of the Earth, in other words, the value of Earth's gravity. Do you remember what they told us about Einstein's elevator at school? If an elevator freely floating in space suddenly started accelerating by 9.8ms^{-2}, a person inside it would be pressed to the floor and think that Earth's gravity had begun to take effect. It works the opposite way too. When an elevator cable breaks on Earth and the elevator cabin falls freely, the people inside it feel weightless. In an isolated system, gravity and acceleration have exactly the same effect."

"Well, I understand that, but if a spaceship is to accelerate continuously, its engines have to work all the time." said Ure. "In a conventional rocket, the engines operate for about ten minutes and then they gradually fall away and the spacecraft flies the final stage on momentum in airless space. And for those crazy ten minutes, hundreds of tons of fuel are needed."

"You don't need to tell me, Ure. I know how a spaceship gets into orbit," said Hooky, defensively.

"In that case, you'll probably also know that your idea is worthless."

"A classic rocket transport reaches its first space velocity within ten minutes, that is, nearly 8 kilometres per second – an acceleration value much higher than the required 9.8ms^{-2}," countered Hooky, defending her idea, "and in doing that it's also overcoming the gravitational force of the Earth."

"Okay, but can you imagine how much fuel you'd need to run the engines for, say, a year?" insisted Ure.

"By the way," laughed Kogy, "when I was pointing out satellites in the night sky to my mum, she thought that the light of the sun reflecting off them was from the fire of their rocket engines."

"This whole debate is pointless anyway," said Hooky impatiently, "I don't want us to use typical chemical fuel."

"So what do you want to use, then?" asked Ure.

"There's only one way to obtain such an enormous amount of energy," said Hooky, taking a sip of water for dramatic effect.

Kogy and Ure both sat looking at her in silence.

The girl screwed the cap back on bottle, and then she slowly mouthed the syllables of the word: "A-nni-hi-lation"

*ms^{-2} means metre per second squared and expresses the rate of acceleration. To give you an idea, if you accelerated at a rate of 9.8ms^{-2}, you would reach 100 km/h in less than three seconds. The most powerful sports cars, for example, accelerate like this..

EQUIVALENCE PRINCIPLE

Imagine an elevator cabin floating motionless in outer space. It suddenly starts to accelerate and the floor flies up towards the person who had been floating freely inside it in a state of weightlessness. After slamming into the cabin floor, that person might come to the conclusion that gravity has begun to take effect inside the elevator (1). Now, let's move to the Earth, or more precisely, its gravitational field. The elevator cabin has just broken free and is falling freely to the ground (2). The person inside finds himself in a state of weightlessness and might spend the final seconds of his life believing he is in outer space. This leads to the following conclusion: **the effects of a uniformly accelerated reference frame and the effects of a gravitational field are the same.** This thought experiment was part of one of the deliberations that led Albert Einstein to develop his general theory of relativity (see page 20).

At first, you might think it's not such a big discovery – the speed of light is always the same and it can never be exceeded, so what? Well, let's imagine a particle of light called a photon that moves, as you might've guessed, at the speed of light. In the opposite direction, a second particle is whizzing towards it at the same speed. The question is – at what speed do they pass each other? In our everyday world, if, for example, two trains were travelling towards each other, we would simply add the speeds together. But we can't do that in this case. The photons pass each other at the speed of light, and it's not possible to exceed that speed. So in this case, we have to express it like this: 1 + 1 = 1. Interesting, isn't it? Now we have something to explain.

SPECIAL THEORY OF RELATIVITY

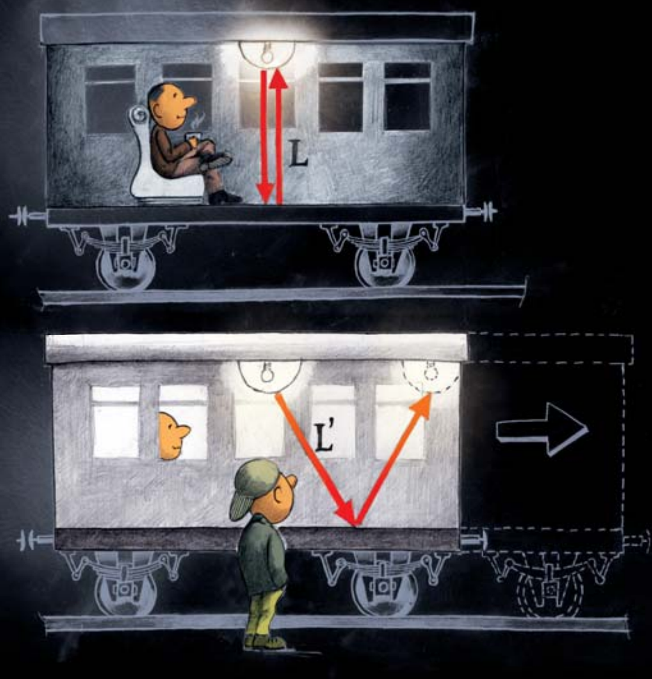
In ancient Greece, there lived a famous scholar named Aristotle, who advocated some very calming thoughts. He claimed that our Earth was firmly anchored at the centre of the universe in a state of complete rest. That kind of world would certainly have suited many people, but two thousand years later, Isaac Newton came along and said that there was no such state of complete rest. If we say that a body is at rest, this statement only applies within a particular reference system. Here's an example – I am lying at home on my sofa. It may be true that nothing is actually moving in the room, but my house is on the Earth, which is rotating around its axis and at the same time orbiting the Sun, which is rotating with the entire galaxy. And the galaxy itself is moving heaven knows where! So, as you can see, thanks to Newton we're not getting much rest anymore. But even Newton in his time was not prepared to grapple with that inviolable quantity of physics we call time. He assumed that time was completely separated from space and that it was always possible to clearly identify a time interval between two events. We could say that he was more or less right, but only up to the point where the speed of a body begins to approach the speed of light.

The first person to express doubts about absolute time was none other than Albert Einstein. As we already know, he assumed a constant speed of light that cannot be exceeded. He came to the following conclusion: if it's not possible to change speed, then everything else must be a variable. So dimensions, mass, and, of course, time all of a sudden became relative. Let's take a look at how Einstein came to the conclusion that the notion of the present was no longer sustainable, and that therefore every moving reference frame must evince its own time.

Imagine a train station in the early evening and a train is passing through it at two-thirds the speed of light. The station master is standing on the platform and a passenger is leaning out of the window. The moment the train passes the station master, the station lights come on. There are two lamps which are, by chance, situated in such a way that each is the same distance from the station master, who is standing exactly halfway between them. The station master will see the two lamps switch on at the same time, but the passenger will claim that first the lamp in the direction of travel lit up before the other one. If we examine the situation in the picture carefully, we come to a shocking realization – both of them are right.

Similar ideas persuaded Einstein to add a fourth dimension to the three-dimensional space coordinate system - time. Thus, he defined the four-dimensional space-time continuum, in short, space-time, from which resulted other remarkable findings. Perhaps the most significant of these is the legendary expression E = mc2, the magical relationship between mass and energy, which, at first, even Einstein himself didn't believe. He actually stated that he wasn't sure if God was leading him on or not. The formula states that not only can mass can be transformed into energy, but also energy into mass. C2 in the formula is the speed of light multiplied by itself, which equals 90,000,000,000,000,000, an incredibly large number. It's therefore possible to obtain an unimaginable amount of energy from one kilogram of matter. The sad truth of this equation was tragically demonstrated by the atom bomb explosions in Hiroshima and Nagasaki.

And now we come to the unsettling sum of 1 + 1 = 1. To clarify this, we need to explain graphically the notion of time dilation or, in other words, time stretching.



Our old friend, the passenger in the train, closed the window, sat back comfortably in his seat, and spent some time pondering the mystery of the station lamps. It was already getting quite dark and the light bulb on the ceiling of the train carriage lit up. It sent out a beam of light that bounced vertically up from the mirror-like floor (which is quite common on trains) and flew back to the light bulb. The passenger saw the beam of light travel a trajectory of 2L. At the same moment, a boy was standing outside, watching the passing train, and also witnessed the bulb lighting up. However, from his point of view, the reflected beam in the moving train travelled a V-shaped trajectory with a total length of 2L'. The beam trajectory seen by the boy was therefore longer than that seen by the passenger in the reference frame of the carriage. But the boy's beam couldn't have flown faster than the beam in the carriage because it would've had to exceed the speed of light. From this situation, we can only draw one surprising conclusion: time is passing more slowly for the passenger on the train.

We can recast this whole discussion into the following beautiful equation, which is derived from the so-called Lorentz transformation. Those who are good at mathematics will easily discover that when we substitute normal speed for v, the difference in time due to dilation is negligible, and when we substitute the speed of light for v, the time difference is infinite (time would stand still on the train). So, in our case, where the boy or station master on the ground grows older by one hour, the passenger in the train travelling at two-thirds the speed of light ages by 45 minutes. We can calculate the length contraction in a similar way. From the passenger's view on the train, time is not passing more slowly – the passenger is able to see from the window the platform gets shorter. If there happened to be another train travelling in the opposite direction to our train, also at two-thirds the speed of light (0.66 c), from the Lorentz transformation equations, the result is that they would pass each other at a speed of only 0.92 c. And if two express trains were travelling towards each other, both at the speed of light, the sum of their speeds would again be the speed of light. And so, that's why 1 + 1 = 1.

$$t' = \frac{t}{\sqrt{1-\frac{v^2}{c^2}}}$$

After Hooky had presented her idea of an interstellar spaceship to the boys, they held meetings in the shed almost every afternoon. They knew very well that mulling over ideas on a journey to the far corners of the universe was nothing more than a bit of fun, but even so they were completely absorbed in working on the construction of the spaceship. In the evenings, their heads were so full of ideas that they were often unable to fall asleep. After several weeks of both calm and heated discussions, Kogy, who was a skilled draftsman, produced at home the first large coloured drawing. The next afternoon, he brought the result of his efforts to the shed, which happened to be the same day a new classmate, Daniel Rubin, joined them.

"It looks like the light fitting in our kitchen," said Ure, commenting on Kogy's creation, and he wasn't far of the mark. The base of the ship consisted of a miniature piece of flat earth of twenty kilometres in diameter, covered by a huge translucent dome. In fact, the ship looked like the world as imagined by some ancient philosophers. Every day a strong source of white light would travel across the dome from left to right to imitate the light of the sun. The day would be programmed to last fourteen hours and the night ten. Beneath the dome, there would be a controlled cycle of water with rainfall, so that the space travellers would be able to cultivate crops for food in the fields. This particular point became a topic of fierce argument. While Hooky imagined that all the astronauts would be vegetarians, Ure complained that if he wasn't allowed to eat sausages, he wouldn't fly anywhere. Hooky eventually shut him up by asserting that there was no real meat in sausages anyway, and that was that.

The flight plan would be as follows: the journey to the nearest inhabited planet would take roughly two hundred years. So, for a hundred years the ship would be accelerating, then the inhabitants of the piece of earth would have to screw their furniture to the floor for a while, turn the ship back to front, and for another hundred years they would be braking.

The key question was where to obtain the amount of energy needed. The only possibility, which had been suggested by Hooky at the outset, was the direct transformation of matter in accordance with Einstein's equation $E = mc^2$. As we know, our world is composed of particles (positive protons and neutrons and negative electrons). But there are other worlds made up of the same particles, but with the opposite charge. If this antimatter were to encounter our matter, they would both disappear in an instant and be transformed into energy, or, more accurately, a gigantic amount of energy. This explosive event is called annihilation. Still, they had yet to solve a few minor problems, such as where to acquire the antimatter and how to store it. Antimatter mustn't come into contact with anything composed of matter, even for a fraction of a second. Ure came up with the idea that a cone of antimatter might float in a vacuum created by means of a strong magnetic field. So, in the engines, matter would react, or rather, annihilate with antimatter in a controlled way, and the energy thus obtained would provide fuel for many decades.

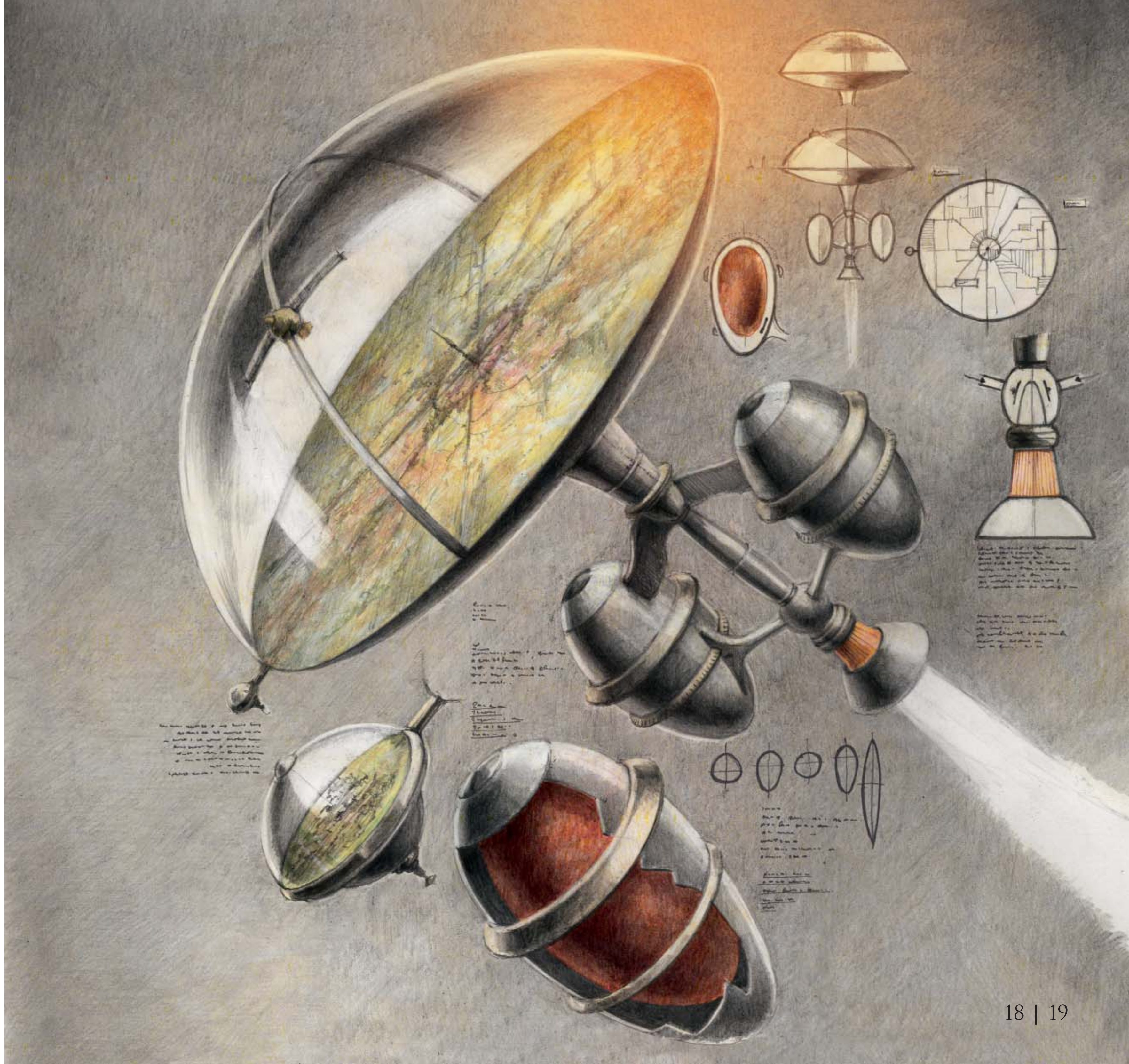
"Two hundred years," thought Kogy, "We'll take off and get practically nowhere in my lifetime."

"The night sky will be so beautiful," dreamt Hooky, "and always different."

"Don't you think that people will start killing each other after spending so much time in that aquarium? What if a war breaks out?"

"That's a good point, the crew must be chosen very, very carefully," said Ure, "For example, hot heads like you, Kogy, shouldn't be allowed anywhere near it."

"Who are you calling a hot head?" shouted Kogy, reaching out for Ure's slender neck.



There are many people who think that the most astounding miracles are to be found in the world of fairy tales. But there is a world where much more incredible things happen, alongside which even the wildest flights of human fantasy pale into insignificance. That world is here, hidden in the fine threads of reality that surround us. This is not an illusion but the truth, which has been discovered and proven by modern physics.

Outside Space may help you begin to uncover some of the mysteries of contemporary physics. It is laid out on white and black pages. The white ones tell the story of a group of young friends, having fun exploring the theoretical possibilities of space travel. When certain unexpected events happen, their innocent games take on a completely different dimension and they are thrust into the midst of a gruelling adventure. On the black pages we learn about the key discoveries in the field of physics over the past hundred years. Although the white and black pages are freely intertwined, the resulting mixture does not remotely resemble anything that can be described as grey.

For children and young people aged 9 and upwards

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