The inspiring life stories of leading scientists as heard on BBC RADIO 4

THE LIFE SCIENTIFIC EXPLORERS

ANNA BUCKLEY

FOREWORD BY JIM AL-KHALILI

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Sanjeev Gupta

FOREWORD

At the time of writing, I have been presenting *The Life Scientific* on BBC Radio 4 for seven fantastic years. I have interviewed Nobel Prize winners, presidents of the Royal Society and Government Chief Scientific Advisors, I have chatted to engineers and inventors, probed the lives and work of astronomers and astronauts, philosophers and psychologists, entomologists, ornithologists and virologists, fungal ecologists, cosmologists, immunologists, primatologists and climatologists. Oh, the list goes on, but I fear you might think I'm just inventing 'ologies' to impress. Basically, if I could remember all the science I have picked up along the way during these seven years, I would be the ultimate science polymath. Sadly, the human brain is only finite (I know that from interviewing neurophysiologists), and anyway I don't have the world's greatest memory. I remember snippets here and there – enough to impress at dinner parties, but that's about all.

Maybe having the scientific lives of my *Life Scientific* guests in a book will help me as a handy reference manual. One thing is for sure, such a book is long overdue. But before I tell you about the author, let me say something about how the programme itself came about.

The Life Scientific was the brainchild of the then new controller of BBC Radio 4, Gwyneth Williams. Gwyneth had contacted me to ask if I might be interested in hosting a brand-new regular weekly science programme that she was keen to commission. The idea, roughly, was that I would chat to other scientists about their life and work for half an hour during that 'golden slot' at 9 a.m., following on from the hugely popular daily news show *The Today Programme*. She pointed out that Tuesday mornings were the only weekday slot without a recognisable long-running weekly programme in the schedule. I was of course very keen. I am sure the hugely experienced production team in the BBC Radio Science Unit were more than a little nervous to have imposed on them a new showcase programme from their new boss, which would be presented by an academic scientist with little radio broadcasting experience. But they knew they had to make it work.

And so the adventure began. From the start, I worked with a number of fantastic producers, and it was a steep learning curve. I remember once being told while in the studio through my headphones to repeat a question, but with a smile. I was puzzled. This was radio; what was the point of smiling. It turns out you can hear a smile, because on radio, everything is in the voice. But one producer in particular has worked closely with me, not only making the programmes but experimenting with the format, style and structure. She is the series producer and also the author of this series of books. Anna Buckley is an extraordinary talent, not only as programme maker but as a synthesiser of information and storyteller. Unlike me, with my unreliable memory, Anna could very well recite every guest we've had on *The Life Scientific* – all 170 of them – and tell you what their scientific discipline is and their claim to fame. It might be my voice you hear on the radio, but it will very likely be Anna who has edited over an hour of chat between two scientists down to a tight 28 minutes of radio gold. It's exciting to see more of her alchemy at work in this excellent book.

Jim Al-Khalili
July 2018

INTRODUCTION

Science is full of surprises, and it's the unexpected twists and turns in these intellectual life stories that I like so much. Serendipity has a starring role. Cue the appearance of a fossilised pine needle that couldn't be ignored.

Who knows what makes us fall in love? Monica Grady was seduced by the minerals in Moon rock. 'The colours were so deep and so clear.' Lucie Green was captivated by images of the sun: 'I do also love the fact that it is a contained nuclear bomb.' When Richard Fortey split open a rock on a beach in Wales as a boy and 'a perfectly formed creature popped out as if it were made for [him]', a lifelong love affair with trilobites began.

The scientists in this volume are all explorers. Inventors, detectives, activists and radicals will follow, although, of course, most scientists are a mix of all these things. Many are at the forefront of discovery, collecting the evidence on which science is based, exploring new terrain. Driven by a desire to conquer the unknown, they are opening up new worlds: from a distant moon of Saturn to the molecules in our DNA. Henry Marsh slices through the 'slightly firm white jelly' that sits between our ears.

They all travel hopefully in their minds. The journey is the reward and there is no talk of giving up. Botanist Sandy Knapp revels in the never-ending nature of her work: 'The more I find out, the more I realise I don't know, so it's a constant voyage of discovery.' Lichenologist Pat Wolseley agrees. She might have been an artist, but it was the questions that drew her back to science. 'And the questions, they never stop.'

The sheer scale of it all can be overwhelming. Distressed to discover that computers couldn't help him to sort a million galaxies according to their shape, Chris Lintott came up with an ingenious solution. He set up a website and asked as many people as possible to do his work for him. Thousands of curious people helped Chris with his PhD. And the idea of citizen science took root in the UK.

Finding things out is fun. It can also be addictive. John Sulston (who sadly died in March 2018) describes the joy of watching cells divide, eight hours a day, non-stop for a year and a half. There was a small hollow in the wooden floor created by the wheels of his chair as he repeatedly moved it back and forth. 'You have to be obsessive to do certain kinds of science,' he said. 'I'm not alone in that.' It took him seven years to sequence the genome of a tiny nematode worm. From there he graduated to human DNA. We have John to thank for Britain's involvement in the Human Genome Project, a feat of biological exploration that has been compared to the Apollo missions to the Moon. A list of three billion genetic letters as they appear on human DNA has been written out in full.

Jocelyn Bell Burnell became obsessed by a tiny smudge in a graph. Determined to understand its cause, she discovered a new kind of star. More than 2,000 pulsating radio stars have been identified since she published her results in 1968. Michele Dougherty persuaded mission control to take a closer look at the magnetic field around one of Saturn's moons when she noticed a strange wiggle in the data that couldn't be explained. Enceladus is now a prime destination in the search for extraterrestrial life.

Several of the scientists featured in this book are involved in the search for life on Mars: 'Primitive life is possible, but it will be very small and difficult to find.' Monica Grady learnt her trade (analysing the chemical composition of meteorites) from the late Colin Pillinger. Colin's *Beagle 2* lander, destined to land on Mars on Christmas Day 2003, enthused the nation. Damien Hirst and the Brit pop band Blur got involved. As did the Queen. 'Every generation needs its gothic cathedrals,' he said. 'We shouldn't be doing things that everyone else has done already.' When the robot *Philae* landed on a speeding comet four billion miles from home in November 2014, it was broadcast around the world, and the chief scientist involved, Matt Taylor, became a media star.

The space scientists were wonderfully down to earth. Brian Cox needs to have his hand held when he crosses the road, according to comedian Robin Ince. He supports the idea that there are many universes, not just one. Quantum mechanics is the way to visit them. The mathematicians Marcus du Sautoy and Eugenia Cheng travel further still, sitting at home or in hotel bars imagining abstract worlds. Why limit yourself to three dimensions (or four if you include time) when you could be enjoying infinitely more?

Some have travelled to the ends of the Earth. Jane Francis loves camping on Antarctic ice. Richard Fortey slipped into the Arctic ocean, weighed down by a rucksack full of rocks. Hazel Rymer measures microgravity on volcanoes. Helen Sharman was the first British person to go into space. Others are more sedate. Having enjoyed plenty of far-flung geological adventures as a young man, Sanjeev Gupta turned his attention to Mars, imagining it could be studied 'in the kitchen over a glass of wine'. He decides where the Martian *Curiosity* rover should go next.

Others travel back in time, recreating vanished worlds. What did our planet look like hundreds of millions of years ago? How were the ancient continents arranged before they came together to form the latest supercontinent Pangaea? Nick Fraser has unearthed some crazy-looking reptiles from the Triassic that make the wacky creatures drawn by Dr Seuss look tame.

I would like you to treat this book like a pick and mix. There is no need to read everything at once. If you develop a taste for science, then my job is done. If you discover something new, I will be delighted. But please don't feel obliged to laboriously understand everything. The point is not to know it all. If Nick Fraser can happily admit that he felt 'out of his depth going back another hundred million years', then so can you. A distressing number of people seem to worry that science is beyond their understanding, but no one understands everything. And, as Eugenia Cheng reminds us: 'You can enjoy an art gallery, without being able to paint.' No prior knowledge is required to read this book.

Working as the series producer of *The Life Scientific*, I have no hierarchy in mind when I sit down on a Friday morning, or wake up in the middle of the night, wondering who Jim should interview next. Science is a collective endeavour conducted over centuries. Anyone who is curious can make a contribution. Who am I to judge one person to be 'more important' than another? Instead, we aim to offer a smorgasbord of scientific ideas and a range of scientists, at different stages in their careers. Their ambitions vary, as does the degree of recognition they have received. Those featured on the programme have been chosen, first and foremost, for the stories they tell.

I have been lucky enough to talk at length to almost all the scientists in this volume, when preparing myself, and them, for their interview with Jim. On more than one occasion, I'm sorry to say, I have phoned a future guest on the programme at the time agreed, exhausted by the stresses of the week and ready to fall asleep. But after talking for an hour, sometimes more, I have often been transformed, energised, exhilarated and inspired by a scientist who has pursued his or her passion with exuberance or quiet zest. I hope that one, or more, of the stories collected in this volume might have a similar effect on you.

AUTHOR'S NOTE

The chapters that follow are based on interviews that were broadcast on *The Life Scientific* between September 2011 and January 2018 on BBC Radio 4, many of which I produced. They aim to capture what was said and something of the spirit in which it was said. They are not comprehensive profiles. Few people's lives fit neatly into 27 minutes and 40 seconds, and I am always struck by just how little can be said in this amount of time. (After seven years of producing *The Life Scientific*, you'd think I might have learnt by now.)

In the earlier episodes we recorded interviews with people who knew the guest or their work and played a clip into the interview for the guest to comment on, so sometimes other voices will pop up. I have also added details and tried to provide necessary context. When preparing for each new interview, I spend days researching the life and work of the guest and hours talking to them on the phone, working out what the story of their life scientific might be. Some of the information gleaned in this way has been included. If you enjoyed listening to these programmes when they were on air, I hope you will find some added value here.

Science moves on, sometimes rapidly, and I am painfully aware of everything that has happened since these interviews were recorded. I forced myself to stay true to the original conversation, but occasionally the opportunity to update the story was irresistible.

MONICA GRADY

‘I am interested in the stories meteorites bring with them’

Grew up in: Leeds

Home life: married to a fellow space scientist; they have a son called Jack and a grandson, Matthew

Occupation: space scientist

Job title: Professor of Planetary and Space Sciences, the Open University, Milton Keynes

Inspiration: seeing Moon rock through a microscope

Passion: extraterrestrial rock

Mission: to open everyone’s eyes to what’s out there

Best moment: ‘There are too many’

Worst moment: getting fired within an hour of being hired for breaking the mass spectrometer

Advice to young scientists: ‘Do what you enjoy’

Date of broadcast: 16 October 2012

Struck by the beautifully coloured minerals in a piece of Moon rock that had been brought down to Earth by Neil Armstrong, Monica Grady became a planetary geologist, specialising in meteorites. Every rock tells a story, and stories from space feel particularly special. She runs the global database of all the extraterrestrial rocks that have been found on Earth and has studied two Martian meteorites in great detail, EETA 79001 and Allan Hills 84001. In a landmark paper in 1989, she announced that organic molecules had been found in EETA 79001, and hopes were raised that there might once have been life on Mars. Microbial, not little green men.

Monica Grady is the queen of alien rock arrivals.[1] 'I've been known as Monica Grady Meteorite Lady for quite some time now,' she said, clearly happy with the description.

For many years, Monica was the curator of the largest meteorite collection in the world at the Natural History Museum in London, which is home to 5,000 specimens. An artist who visited Monica at the museum described her as 'a bit like a meteorite herself. She was just so full of energy. She seemed to know all their stories, which was mind-bending. They were like her children.'

'I don't know about that,' Monica said, laughing, 'but they're certainly more obedient than my son.' The rocks 'sit there and do what they're told'.

As a child, Monica enjoyed exploring the Yorkshire Dales. 'It doesn't take you long to find a limestone pavement,' she said. Walking on the wobbly blocks of weathered rock at Malham and avoiding the hazardous grykes between them, Monica, aged eight, wanted to know what had made this other-worldly landscape. How had it come to be the way it was?

'Were you bringing rocks home, even then?' Jim asked.

'I was bringing home lots of bits and pieces, yes. All sorts of things – the odd fossil that I found, bits of shell. For ages and ages and ages, I had a bit of sea-washed glass that I'd found on the beach.' She imagined this pretty stone was a precious gem and only discovered much later that it must have started life as piece of broken glass.

In the final year of her joint honours degree in chemistry and geology at Durham University, a lecturer arranged for the students to see a slice of the Moon, courtesy of a teaching pack donated by the *Apollo 11* mission. Thinly sliced, polished and placed under a strong polarising microscope, Moon rock looked magnificent. 'The colours were so deep and so clear, beautiful cerise and turquoise, and pink and yellow and beige and grey,' Monica said, her voice becoming soft and dreamy. The rock was a patchwork of sophisticated translucent colours, shining brightly. 'Some of them were a bit cracked but you can see such sharp outlines of the crystals.' There were clusters of crystals with sharply defined edges, like limbal rings around an iris.

The rock she was looking at had come from magma, 'from a lava that's crystallised'. And she could 'see how all the grains fit together so beautifully'. It was stunning aesthetically and a scientific coup – a close-up of the Moon. 'Those thin sections of the *Apollo* rocks were what really inspired me,' she said.

'Do you ever find yourself looking at the ground, hoping to find meteorites?' Jim asked.

'Oh yes,' Monica exclaimed. 'All the time!'

There could be meteorites anywhere on Earth and Monica has joined many meteorite-hunting expeditions. Antarctica is a particularly good place to look. Blackened meteorites on white ice are hard to miss, and the arid conditions mean the meteorites are well preserved.

'Can you tell, just by looking at it, where a meteorite has come from?'

'I've got a very small chip of one here,' Monica said, whipping a small rock out of her pocket. 'See if you can look at it and tell me where you think that one came from?'

'Can I hold it?' Jim asked, taking off his glasses. 'Well, it's a little black piece of rock,' he said. 'It's very shiny. Half of its surface is very black, which presumably is where it's burnt, coming into the atmosphere . . .'

Monica could wait no longer. 'This one's come from Mars,' she said.

'How exciting!'

'Don't drop it!'

'How much is it worth?' Jim asked. 'Can I keep it?'

'No, you can't keep it!' Monica exclaimed, reaching forward to grab it back. 'And I'm not telling you how much it's worth. It's scientifically priceless.'

Some meteorites contain 'dust from the beginning of the solar system'. Viewed from the outside, they are nothing special. The burnt remains of their journey through the Earth's atmosphere cover the surface with a blackened crust. But when they are split in two, the insides can be marvellous.

Monica encouraged Jim to look more closely at the Martian meteorite he coveted, 'a piece of a rock from a volcano on Mars which has solidified'. 'When you look closer inside,' Monica said, 'you can see minerals that have been formed by water running across the surface of Mars. You've got these secondary minerals called carbonates.'

'And this is what you do?'

'This is what I do. Yes.'

When studying the chemical composition of the minerals found in meteorites, Monica is particularly interested in carbon. 'Life is based on carbon,' she explained. 'Life is based on the DNA molecule,' she added more precisely. 'I'm not looking for DNA. I'm looking for the original bits that would go together to make a DNA molecule.' In other words, one or some of the five elements from which the DNA molecule is made: carbon, oxygen, hydrogen, nitrogen and phosphorus.

'The very first stages?' Jim said.

'The first stages, yeah. Building blocks.'

'It all sounds very sensible, but how sensible is it to even expect to find life on Mars?' Jim asked. 'After all, it is pretty inhospitable.'

'Mars is an inhospitable, cold, arid planet now,' Monica replied. 'But it wasn't always like that.' And planet Earth hasn't always been the paradise for life that it is now. 'For the first 2 billion years of Earth's history, there was nothing there. There were no major life forms.' As the Earth cooled, its atmosphere thickened and the surface of the Earth 'became really good, full of these hospitable niches where life could get going'.

It was a different story on Mars. Being just over half the size of planet Earth, the gravitational pull Mars exerted on its atmosphere was weaker, and when Mars cooled it lost its atmosphere and was no longer able to retain any surface water. And at that point in Martian history, 'the possibility of evolved complex life forms arising on Mars more or less disappeared.'

'So, going back several billion years, just as there were primitive life forms on Earth, there could well have been similar life forms on Mars?'

'When life was getting going on Earth, life could have been getting going on Mars,' Monica confirmed. 'That is the hope that keeps people looking.'

Traces of these ancient life forms have been found in terrestrial rocks. What Monica and others want to know is: can similar traces be found in rocks on Mars? The question sounds simple enough but, as Monica said: ‘It’s not an easy search.’

‘When life was getting going on Earth, life could have been getting going on Mars. That is the hope that keeps people looking’

When Giovanni Schiaparelli noticed a neat series of lines on the surface of Mars in 1877, he imagined aliens building canals to irrigate their crops, and the possibility of life on Mars has created waves of excitement ever since. At the beginning of the twenty-first century, our hopes of finding life on this inhospitable planet have been revitalised once again.

‘Why is that?’ Jim asked.

‘It’s because we know so much more about life on Earth.’ Bacteria have been found living in black smokers at the bottom of the deepest oceans, thriving under enormous pressure in superheated hydrothermal fluids. We have discovered organisms surviving in severely acidic and dangerously alkaline conditions, on a par pH-wise with battery acid and bleach.

Just knowing Earth-bound extremophiles exist makes looking for life on a planet as inhospitable as Mars feel a little bit less flawed. Conditions that were once thought to be lethal to life have been shown to be habitable, at least for certain life forms.

‘When scientists say they’re looking for life on Mars,’ Jim said, ‘what kind of life are they talking about?’

‘I’m sorry – I must say this. It’s life, Jim, but not as we know it!’ Monica laughed. ‘I’m so, so sorry. I couldn’t resist!’

In fact, scientists are looking for life ‘as we know it’ – carbon-based and dependent on water. ‘We’re looking for microbial life,’ and it’s not going to be easy to find. ‘It will be microscopic.’ It’s going to be in hidden niches, beneath the ice or in shady cracks. ‘It’s going to be below the ground. It’s going to be in caves.’ It might live under sheets of ice. Anywhere that offers protection from the intense electromagnetic radiation in space. ‘It’s going to be hidden from ready view.'

'And presumably it's going to be trapped in rocks?'

'Yes. There will be evidence for it trapped in rocks. There might be evidence for it in ice.'

'Could there be life on Mars today?' Jim asked.

'Primitive life on Mars is possible,' Monica said. 'But it will be very small and very tricky to find.'

'So primitive microbes, not little green men?'

'I suspect, and most people suspect, that that is the case,' Monica said. 'Mars is not the kind of place where you would expect to find highly evolved life.'

'Mars is not the kind of place where you would expect to find highly evolved life'

Monica spent most of the 1980s studying Martian meteorites EETA 79001 and ALH 84001.[2] She was working at the Open University at Milton Keynes with Ian Wright (a fellow geologist who liked to wear his jumpers inside out and who later became Monica's husband) and Colin Pillinger.

In 1989, this close-knit and energetic team described the existence of organic molecules in Martian meteorite EETA 79001 and published a paper in the prestigious peer-reviewed journal *Nature*. Five years later, they reported a high concentration of complex organic molecules in the Allan Hills meteorite as well. These are the molecules without which life, as we know it, is not possible.

Two years later, in 1996, a team of US scientists who were also working on ALH 84001 went one step further. Writing in another respected journal, *Science*, the team (which included one scientist who had previously worked with Monica, Ian and Colin) announced that they had found evidence of primitive life on Mars. The media went mad about their claims to have found a Martian microfossil.

The Stanford University Press Team tried to put things in perspective: 'If a thousand such fossils were lined up in a row they would span the dot at the end of this sentence.’ Nonetheless, evidence of a Martian microbe, a hundred times smaller than a human hair, that had been dead for more than 3 billion years, was celebrated as if we had seen little green men digging canals.

Monica was sceptical. Finding microfossils in terrestrial rocks is hard enough. ‘I thought it was rubbish,’ she said, langhing. But then she added, more seriously, ‘each thread of evidence is interesting’.

She disagreed with the way the US team had pieced the evidence together. The leap from complex organic molecules to microfossils is enormous, in terms of biological evolution, and Monica did not find sufficient evidence to support the idea that such a leap had been made. It seemed to her to be a case of 2 + 2 = 5. And she wrote a response to the paper in *Nature* entitled ‘Opening a Martian Can of Worms?’

Monica, Ian and Colin had described a concentration of complex organic compounds that was unusually high for a Martian meteorite but had stopped well short of claiming the existence of biogenic material.

‘I still don’t believe it,’ Monica said. But it’s rare for the study of meteoritics to get quite so much media attention, so it wasn’t all bad. ‘Without doubt it attracted attention to astrobiology,’ Monica said, laughing. ‘It opened the doors to funding. So, in that sense, it was wonderful!’

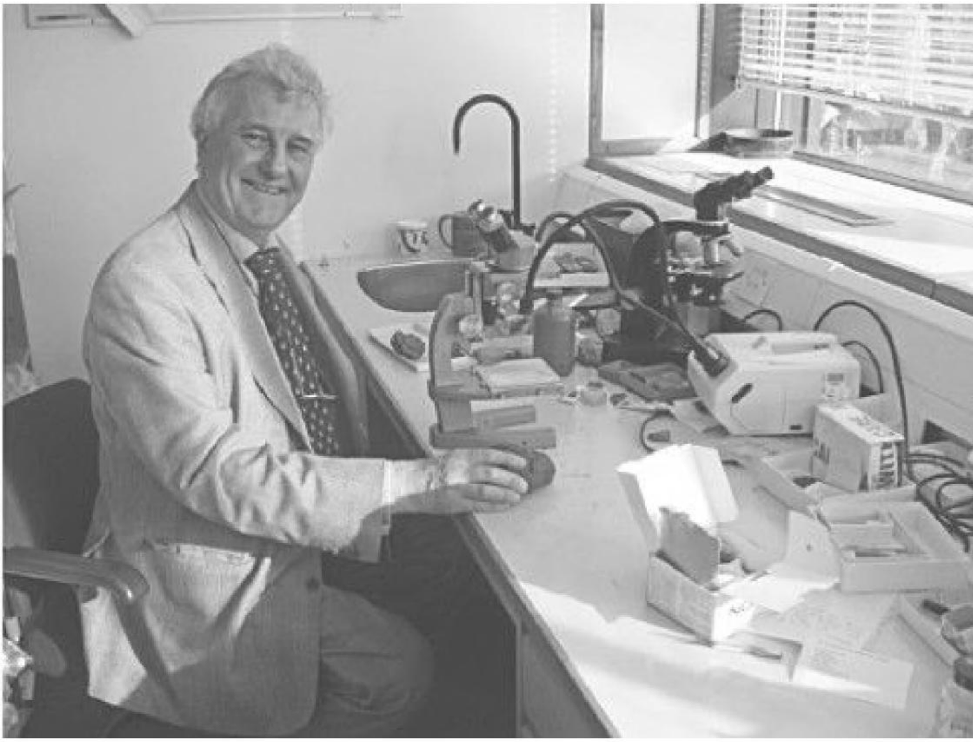
Jim wondered if Monica had felt upstaged by the team in the USA. ‘I can’t help thinking if I were in your shoes at the time, I’d be panicking ever so slightly that they’d completely trumped me and my work.’

‘I didn’t find the fossil in the rock because I wasn’t looking using that particular technique,’ Monica said. ‘And to be quite frank, I don’t believe in one scientist trumping another scientist. This sounds hugely idealistic, but I think as long as somebody gets to the story, it doesn’t really matter who does.’

‘What’s the verdict now on that fossil?’

‘The verdict on that fossil is, we still don’t know. It hasn’t been ruled out, but there’s more and more work going on.’

She was being polite. There are very few scientists today who would claim that the Allan Hills meteorite contains evidence of primitive life.



Courtesy of Richard Fortey

RICHARD FORTEY

'A creature that was hundreds of millions of years old popped out perfectly as if it was made for me'

Grew up in: west London
Home life: married with four children
Occupation: palaeontologist
Work address: Natural History Museum, London
Inspiration: finding a perfect fossil specimen, age 14
Passion: trilobites
Mission: to recreate vanished worlds
Best moment: presenting a paper on trilobites at a conference on plate tectonics
Worst moment: falling into the Arctic ocean weighed down by a rucksack full of rocks
Advice to young scientists: persist
Date of broadcast: 28 October 2014

Richard Fortey is enthralled by trilobites, ancient marine creatures that look a bit like woodlice. For half a century he has studied little else. He found his first specimen on a beach in Wales when he was a teenager. As a student, he joined a geological expedition to Spitsbergen, in the northernmost part of Norway, and made a remarkable discovery: hundreds of previously unknown species of trilobites were buried in limestone that was 470 million years old. He spent several years reassembling their fragile fossilised remains, studying the anatomy of different species to gain clues about how and where they lived. And, aware of some intense debates about how landmasses had moved over deep geological time, he then used his knowledge of trilobites to broaden our understanding of plate tectonics.

Fortunately, David noticed and grabbed him with an outstretched arm before his head went under. 'He was freezing and hardly able to walk,' David said. 'Mercifully, he made it back to camp where he dried out, and that night we drank to life.'

On his return from Norway, Richard worked in the Sedgwick Museum in Cambridge and spent most of the next five years chiselling out trilobites from the Spitsbergen rocks and extracting specimens, relentlessly mixing and matching different trilobite bones, assembling head shields and cheekbones, segments of spines and broken legs (on the rare occasions that these delicate limbs had been preserved), trying to re-create the skeletons of these ancient creatures and identify different species.

Working in this way, taking care to avoid any inaccurate misfits, he discovered over a hundred species buried in the Spitsbergen rocks, including several that were new to science. 'This particular place in Spitsbergen' contained a proliferation of different species. 'It was very fortunate,' he said. He described as many of them as he could so that future generations of trilobite hunters who might unearth similar remains would know what they had found, and he named several new species, including *Opipeuter inconnivus* 'the one who gazes without sleeping' (a name that perhaps reveals more about his state of mind at the time, than it did about the trilobite in question).

Then he started to try 'to deduce how these animals actually lived', paying particular attention to their eye sockets. Trilobites have the first well-preserved visual system in the fossil record. 'It's quite amazing how much can be discovered about the way they saw the world through those eyes.'

It had been assumed that all trilobites lived on the sea floor, partly because the specimens that had been found pre-Spitsbergen tended to be flat, and partly because their eyes only seemed capable of looking up. But the specimens that Richard found in Spitsbergen led him to question this assumption. He came across trilobites of all shapes and sizes. Some were quite rounded, and several had huge globular eyes. Eyes that would be capable of looking in every direction, he imagined. Sea-floor dwellers don't need to look down, but for creatures that are surrounded by water, 360-degree vision can be useful. Mainly for this context'. But perhaps not everyone would have made this leap. By looking at the global distribution of the many and varied species of Ordovician trilobite, Richard found 'a different way of getting at the ancient geography'. All of a sudden, all the careful work he'd done, determining how and where different species of trilobite must have lived, came into its own. His ability to differentiate between deep-sea divers and shallow-sea swimmers (which had been interesting and of value in itself) now provided him with vital clues about the whereabouts of these ancient continents.

He created maps showing the relative abundance of different trilobite species. Wherever there was an abundance of shallow-water species, there must have been shallow seas, and shallow seas, Richard reasoned, are found on the edges of continents (not in the deep oceanic trenches between them). By this straightforward but inspired logic, he was able to map out the boundaries of these ancient continents, using the shallow-water trilobites as his guide. And as everyone who has ever been confronted by a difficult jigsaw knows, the edge pieces can be a good place to start. The existence of deep-water trilobites in the sediment indicated the main body of an ocean; and an absence of trilobites meant that the rocks must have been on land, not under the sea.

Before long, he was presenting papers at international conferences about plate tectonics (a hot topic in the Earth sciences in the 1970s). He escaped the trilobite ghetto and found a platform from which to share his trilobite expertise. Convinced by the power of his trilobite evidence to describe the landmasses that existed before Pangaea, he was determined to show the world just how useful his specialist knowledge could be. And he argued robustly with anyone who had a different picture of the ancient *Mappa Mundi* from the one that the trilobite evidence suggested.

'New results and controversies were happening all the time and getting resolved,' he said. 'We did have several quite big battles between different fields of science, and generally speaking, the palaeontological evidence held up pretty well.'

'We did have several quite big battles between different fields of

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The randomness of radioactive decay gave us the first clue. Werner Heisenberg sealed the deal. His Uncertainty Principle (which states that you can know either the position or the momentum of a subatomic particle, but never both) shocked everyone. Even Einstein was unhappy. 'God does not play dice,' he pronounced. But as the flamboyant, brilliant and much-admired (by Brian and millions of others) Richard Feynman said, subatomic particles 'do not behave like waves, they do not behave like particles, they do not behave like clouds or billiard balls, or weights and springs, or anything that you have ever seen.' And the laws that govern them are unfamiliar too. They are described, not by Isaac Newton, but by Max Born.

The Born rule describes the probabilistic nature of our universe at its most fundamental level. It allows us to calculate the possibility that a particle will be in a particular place (based on measurements of time, mass and distance).

'And you can compare that with experiments, and it works.' Phenomenally well. Brian once claimed that the rules of quantum mechanics can be written on the back of an envelope, so Jim invited him to do something similar.

'So, Brian Cox, without hesitation, repetition or deviation, can you explain, as succinctly as possible, the rules of quantum mechanics? Your time starts now'

'Well, the most basic version I know of it is Feynman's version, which essentially says particles are particles and they hop from place to place with a particular probability. And the probability that a particle that's at one place will be at a different place later is given by a very simple rule. It uses a quantity called the action which is to do with the mass of the particle, and the time and the distance. So, you basically calculate these little quantities – you add them up.

'So, I start with an electron in one corner of the room, and I *image not available*

quantum mechanics accurately described subatomic reality. Many had waited many years for this moment.

'It was one of the most remarkable feelings I've ever had,' Brian said. 'You type in all these things, all your theory. You make predictions and you look at these collisions. And they just match in every detail. They match the theory.' Joy! This was the experience, Brian told Jim, that made him understand the power of science.

> *'You type in all these things, all your theory. You make predictions and you look at these collisions. And they just match in every detail. They match the theory'*

All good science experiments are written up in the same way: method, results, conclusion. This is what we know so far about the Large Hadron Collider experiment. The method (colliding hadrons) works. Smashing protons together in particle accelerators has liberated quarks and other subatomic particles, and we have found ways to measure how many of these exotically named particles behave. There is no shortage of results. Now all that's needed is a conclusion. And on this, physicists disagree. Often quite profoundly.

Brian and his good friend and colleague Jeff Forshaw have worked together for many years and have written several books together about what happens inside atoms.

'We're almost exactly the same age, and we were born geographically roughly in the same place,' Brian said. And, perhaps most important of all, 'We think in the same way about physics.'

Despite all their similarities, even they don't always see eye to eye about what it all means. 'We were working on one of our science books,' Jeff said, 'trying to get our head around

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