SHORTLIST
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Massive

The Hunt for the God Particle

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CHAPTER 1

Long Road to Princeton

The drive up to Princeton could take the best part of a day and that was if you were lucky. The route followed the coastline up the eastern seaboard, around the broad expanse of Chesapeake Bay, and on to Washington, Baltimore and Philadelphia, before finally arriving in the town that was once home to the greatest physicist of all, Albert Einstein.

Peter Higgs packed some clothes and a folder full of research notes and went out to the car with his wife, Jody, and their six months old son, Christopher. He swung the suitcase in the back and had a long look at the road map. Satisfied with the directions he pulled away, working north and east through the tree-lined streets and out towards the freeway as the town eased itself to life beneath the spring morning sun.

It was 14 March 1966. Higgs, a physicist at the University of Edinburgh, had moved to Chapel Hill in North Carolina the previous year for a sabbatical at the town's university.[1] His work there had caught the eye of a prominent scientist who invited him to give a seminar at Princeton's Institute for Advanced Study, one of the world's leading intellectual centres and the place where Einstein himself had spent much of his working life. The seminar was destined to be controversial: Higgs had discovered what became known as the origin of mass.

The trip turned out to be more than just another academic visit. It marked the beginning of a run of events that catapulted Higgs into the scientific limelight and set the stage for the greatest hunt in modern physics. Using multibillion-dollar machines that occupied miles of underground tunnels, thousands of scientists spent decades looking for a particle that formed the linchpin of Higgs's theory. Their mantra was simple: find the Higgs particle and the mystery of the origin of mass was solved.

For centuries, scientists had no idea that mass even had an origin, at least not in the modern sense of the phrase. The word *mass* described how much matter an object had, and *matter* was no more than a grand term for 'stuff'. A lump of rock had more mass than a loaf of bread (unless the baker was having an off-day), and that was that. The meaning of mass was so intuitive and tangible that no one seriously thought to question it.

Vague and incomplete notions of mass emerged in antiquity and were developed through the Middle Ages. Giles of Rome, a prominent theologian and one of the most influential thinkers of the late thirteenth century, took an important conceptual step when he distinguished between the dimensions of an object and the amount of matter it contained.[2] A block of ice, for example, clearly changed shape when it was melted into water, evaporated into steam, condensed and frozen solid again. Yet the amount of matter remained the same, he said, whichever form it was in. The observation, which surely made for lively theological discussions about transubstantiation, mirrors the modern definitions of volume and mass.

In the early fourteenth century, the Parisian philosopher Jean Buridan drew on the concept of mass when he described how throwing an object gave it an impetus that depended on how much matter it contained and the speed at which it was lobbed.[3] The sixteenth-century German astronomer Johannes Kepler took things further, by arguing that planets stayed true to their orbits and didn't hurtle around space like scattered snooker balls thanks to the inertia arising from their enormous masses.

Despite the valuable work of early philosophers and astronomers, the term *mass* was not used systematically until 1687, when Isaac Newton laid the foundations of classical mechanics in a great but wholly impenetrable work, the *Principia*.[4] Newton said mass was a quantity of matter, which arose from an object's volume and density. An object's mass governed its inertia, or how much it resisted being pushed around, and also how strongly it felt the force of gravity. With these definitions in place, Newton derived the basic laws of motion.

Newton had an intuitive grasp of mass and matter that went far deeper than he let on in the *Principia*. Worldly objects, he believed, were made up of countless tiny particles that were created by God and could never be destroyed. The particles came in different forms and sizes that stuck together to make different materials. All man could hope to do was fashion new shapes and forms from these conglomerations of vanishingly small particles.

Nearly twenty years after the *Principia* was published, Newton allowed himself to speculate on the nature of matter in his next great work, the more accessible *Opticks*: 'It seems probable to me, that God in the beginning formed matter in solid, massy, hard, impenetrable, moveable particles . . . so very hard, as never to wear or break in pieces,' he wrote.[5]

Newton's musings on matter were not so far off the mark. Today, scientists think of matter as being built up from a handful of particles that are almost indestructible. It took scientists more than half a century to identify the most basic building blocks of matter, which come together to form the innards of atoms. Variations of these give us the chemical elements of the periodic table: atoms that form metals, crystals, liquids and gases, and intermingle to make an almost endless list of molecules.

Scientists call the ultimate building blocks of matter fundamental or elementary particles and by definition they cannot be broken up into smaller pieces. The first was discovered in 1897 by J J Thomson at the Cavendish laboratory at Cambridge University.[6] Thomson, like many physicists at the time, was intrigued by the nature of glowing rays that appeared when a voltage was applied across glass tubes filled with low-pressure gases. The rays moved from the cathode, which is the negatively charged electrode, to the anode, which is positive. What the rays were made of was a mystery.

Thomson began a series of experiments to investigate these curious 'cathode rays'. In one, he used a 15-inch glass tube coated at one end with phosphorescent paint. Thomson modified the anode by creating a slit in it, so some of the rays coming from the cathode would pass through it and make a bright spot when they hit the phosphor. His masterstroke was to build into the glass vessel a second set of electrodes that the rays passed through. When Thomson linked the electrodes up to a battery, he found the spot darted away from the negative plate and towards the positive one.

Further experiments showed that cathode rays were composed of streams of tiny, negatively charged particles. Thomson named them *electrons*, a term introduced by the Irishman George Johnstone Stoney twenty years earlier, and suggested they were ubiquitous ingredients of all the atoms scientists knew. Emboldened by his discovery, Thomson proposed the 'plum pudding' model of the atom, so called because it pictured atoms as positively charged balls of matter dotted with tiny negative electrons.

It turned out that Thomson's atomic pudding was not what Nature ordered.[7] The idea fell apart when the New Zealand-born chemist and physicist Ernest Rutherford announced the startling news that atoms were mostly empty. Instead, he said in 1911, almost all of an atom's mass is bundled up in a central, positive nucleus. Later that decade, Rutherford probed the nucleus more deeply and found evidence for a new kind of particle within, the positively charged proton.

By the mid-1930s, physicists had what they believed to be the main building blocks of matter. The nucleus of an atom was made up of protons and (except in the case of hydrogen, the simplest atom there is[8]) another type of particle, the uncharged neutron, discovered in 1932 by the English physicist James Chadwick.[9] Surrounding the nucleus was one or more negatively charged electrons. This interpretation was on the right track, but it was incomplete. Scientists later discovered that protons and neutrons were not elementary particles of matter at all. Unlike the electron, protons and neutrons are made up of even smaller particles called *quarks*.

It took a long time for physicists to accept that quarks were real, not least because no one had ever seen one. The American physicists Murray Gell-Mann and Georg Zweig first put forward the idea in 1964, though they hit on the theory separately.[10] They realised that the behaviour of protons and neutrons made sense if each contained a trio of quarks. The proposal was still contentious when Peter Higgs visited the Institute for Advanced Study in 1966.

Quarks were only widely embraced as true elementary particles of matter some years later.

In the half-century or so that followed Thomson's work on the electron, physicists identified around 200 different kinds of particles, most of which were pairs or triplets of other subatomic ingredients.[11] The proliferation of particles was getting confusing, but order came in the mid-1970s with what must rank as the crowning glory of particle physics. Known as the Standard Model, a name so prosaic it is almost an offence, it explains all known matter from just a handful of truly elementary particles.[12]

According to the Standard Model, there are twenty-four fundamental building blocks of matter. Among them are six kinds of quarks (called up, down, top, bottom, charm and strange), which come in three varieties depending on a property known as their colour charge.[13] The colour charge can be red, green or blue, but the names have no meaning in the visual sense. Quarks with different colours attract one another. The remaining six matter particles are called 'leptons', a family that includes electrons and ghostly, nearly massless particles called neutrinos, which pass almost unhindered through anything in their path. In our universe, the stable matter we know of is based on quarks and electrons.

The other particles described by the Standard Model are not building blocks of matter, but are there to do other jobs. Four of them are responsible for transmitting forces of nature and are known as bosons.[14] You don't fall through the floor because of the electromagnetic force, which is carried by photons, which are simply particles of light. Inside atomic nuclei, quarks are stuck together by the 'strong force', which is carried by particles aptly named gluons. Other particles, called W and Z bosons, carry what is known as the weak force, which goes to work when certain radioactive elements decay.[15] One more particle completes the Standard Model, a theoretical particle predicted by Peter Higgs's theory, known as the Higgs boson.

You could be forgiven for thinking that the Standard Model wrapped up all there was to say about the origin of mass. If all stable matter we know of is made up of quarks and electrons, then surely these elementary particles embody the smallest units of mass possible? By that reckoning, they *are* the origin of mass. You could work out how much mass any object had just by totting up the contributions from all the zillions of quarks and electrons inside. It turns out it's not that simple.

When sums go wrong from the beginning, it usually means you are missing something. Here's a case in point. A proton contains two up quarks and one down quark. If you add up the masses of the three, the total comes to just 1 per cent of the mass of the proton. A full 99 per cent of the proton's mass is unaccounted for. The same thing happens with the neutron, which contains one up quark and two down quarks. If Newton had had the last word on mass – that it was simply a measure of matter – then totting up the masses of the quarks should give the right answers. But Newton knew only part of the story. The missing mass came from somewhere else.

There is more to mass than meets the eye. How much more became clearer in 1905, when a 26-year-old Albert Einstein, while holding down a day job at a patent office in Bern, Switzerland, published a paper entitled 'Does the inertia of a body depend on its energy content?' To ruin the ending, the answer is yes. Einstein showed that mass and energy are interchangeable, that mass can be considered a measure of how much energy an object contains. For the scientific establishment, the idea was a bolt from the blue, but it is an unavoidable consequence of Einstein's so-called special theory of relativity.[16] The equation Einstein derived was $m = E/c^2$, where an object's mass equals its energy divided by the speed of light squared. Rearranged, the equation becomes the all-too-familiar $E = mc^2$, where the giant value of the speed of light (close to 300,000 kilometres per second) makes it easy to see how even tiny masses embody vast amounts of energy.

Einstein's revelation goes some way to explaining why the proton's mass is greater than the sum of its parts. The three quarks inside a proton account for only 1 per cent of its mass, but they are held together by extraordinarily strong forces. The bulk of a proton's mass comes from the energy locked up in the movement of the quarks inside and forces that bind them together. It leads us to a remarkable truth: any object you care to mention, from your pet dog to your mobile phone, owes most of its mass to the intense energy it takes to keep it in one piece.

The interplay between mass and energy that Einstein highlighted is demonstrated beautifully inside giant particle accelerators that physicists use to study subatomic particles. Slam two particles together at sufficiently high speeds and the debris from the collision is likely to contain heavier particles than you started with. The energy released when the particles collide almost instantly condenses into fresh matter.

Between them, Newton and Einstein laid the foundations of our understanding of the nature of mass, but in the 1960s it was clear something was still missing. Scientists could not explain where the fundamental particles got their masses from. It was this mystery that Higg's theory seemed to solve. It gave scientists their best hope yet of fully describing the mass of everything they knew.

Peter Higgs arrived in Chapel Hill to set up home on 6 September 1965, having left Jody, who was heavily pregnant at the time, with her parents in Urbana, Illinois. At the university, he set about writing his first major paper on the origin of mass. On 24 September he was working in the library of his new department when he was called to the phone. His first son, Christopher, had just been born.

Higgs finished the paper in November and sent a copy for publication and a few more to physicists he thought might be interested. Though it wasn't clear at the time, Higgs's theory pointed to a critical moment in the birth of the universe. It showed that, in the beginning, the building blocks of matter weighed nothing at all. The elementary particles were entirely massless. Then, a fraction of a second after the big bang, the cataclysmic explosion that flung the universe into existence, something happened.[17] A previously unknown energy field that spread throughout space switched on. In that instant, massless particles that had been zipping around at the speed of light were caught in the field and became massive. The more strongly they felt the effects of the field, the heavier they became.

Time began 13.7 billion years ago with the first bang there ever was.[18] The universe, then a microscopic ball of intense energy, was too hot for the laws of nature as we know them to emerge. But in the blink of an eye (had there been one around to oblige) the cosmos grew to the size of a beach ball and cooled just enough – to around 10 thousand trillion degrees Celsius – for the Higgs field to come to life. In that instant, the first building blocks of matter were tamed, made heavy and slow, like flies in soup.

The Higgs field is crucial to the structure of the universe and its ability to support life as we know it. Without the field the elementary particles, the building blocks of matter, would behave like light. The chemistry we are familiar with would not be possible.[19] Matter would not clump together into the atoms we see today. Stars and planets would not have formed. Our solar system would be a lifeless wasteland, and so would those in other parts of the universe.

At the heart of Higgs's theory was a new particle associated with the mass-giving field. The so-called Higgs boson is, in a sense, part of the field that is left over once it has given mass to particles.[20] The best hope scientists have of proving Higgs's theory right is to show that the particle exists.

Not long after Higgs sent his paper out to academics, a letter arrived at his office in Chapel Hill. It was from Freeman Dyson, the English-born mathematician who had worked at RAF bomber command in the Second World War. Dyson had crossed the Atlantic at the age of 23, clutching a letter declaring him the best mathematician in England. He had since become an eminent professor at Princeton's Institute for Advanced Study.

Dyson's letter was amiable and could not have been more flattering. He explained how he'd enjoyed Higgs's latest paper and that it made clear things he'd been puzzling about for some time. He asked if Higgs would give a seminar on his theory at the institute that spring. Higgs was astonished but accepted without a second thought.

Dyson's enthusiasm for Higgs's work didn't mean he was in for an easy time at the Institute for Advanced Study. The institute was home to some of the brightest physicists in the world and they were certain to disagree with Higgs's theory. Renowned scientists had flocked to the institute since Louis Bamberger, an American philanthropist, established it in the 1930s. Its most famous resident, Albert Einstein, spent the last twenty-five years of his life there, trying to explain how the forces of nature were born. The Austrian-American logician Kurt Gödel was there too, redefining the limits of human knowledge and vexing Einstein by pointing out that his famous theories allowed time travel to be possible.[21] The father of modern computing, John von Neumann, was also at the institute, turning the mathematics of poker into a political strategy to win the Cold War.[22]

The towering figure of Robert Oppenheimer, who had led the Manhattan Project to build the atomic bomb, had become head of the institute in 1946, and only added to the intimidating aura of the place. Oppenheimer was renowned for his short temper and sharp tongue and could be at his worst when he turned up for the weekly seminars that were held on the campus. It wasn't unknown for him to bully less self-assured speakers, quizzing them relentlessly and correcting them before they had a chance to respond. It was a character trait Dyson despised and it occasionally triggered rows between the two men when seminars were over. 'Oppenheimer always tried to tell you what you would have said if you were as clever as Oppenheimer,' Dyson told me.[23]

As Higgs drove on, his mind wandered to the talk he would give the following day. The audience would be unlike any he had spoken to before. When Higgs returned his attention to the road, he was gripped by a surge of panic.[24] Afraid he was about to lose control of the car, he pulled over. On the side of the road, he took a few deep breaths and tried to regain his composure. Higgs had just seen a road sign. The exit for Princeton was only a mile ahead. He was nearly there.

The Institute for Advanced Study sits amid 800 acres of landscaped gardens, a mile outside Princeton. Instead of driving directly there, Higgs took a detour into the town and parked his car. He found his way to a post office and had a word with the clerk. From behind the counter, the man produced a first day cover of the violet 8 cent stamps that had been issued that day in commemoration of Einstein's birthday (he had been born on that date in 1879). Each carried a picture of the great physicist taken twenty years earlier by Philippe Halsman, a family friend who had served time in an Austrian prison for killing his father on an Alpine hike. The stamps irked Higgs because they referred to Einstein as a 'prominent American'. Although Einstein had taken US citizenship in 1940, Higgs considered him a European at heart. Nonetheless, he thought the gift would go down well with his friend and mentor Nicholas Kemmer back in Edinburgh and he duly posted it back to Scotland.

It was approaching evening when Higgs pulled up at the institute, where he and Jody met Freeman Dyson. The three got on well and Higgs soon forgot the nerves that had overcome him on the drive there. When they were done chatting, the Higgses went to their lodgings and collapsed into a much needed sleep.

Higgs's talk was scheduled for 4.15pm the following afternoon. When he arrived he saw Dyson himself was down to speak first. The talk was highbrow, on the stability of matter, but it addressed a simple enough question: how is it that the objects around us stay intact considering they contain countless particles held in place by finely balanced yet extraordinarily powerful forces? Why doesn't this book, with the enormous amount of energy locked up in its atoms, suddenly tear itself apart? Why don't your clothes spontaneously explode into a zillion subatomic fragments?

Dyson wrapped up his brilliant lecture and opened the floor for questions. As expected, the audience was sharp and challenging. Their skills had been honed by something of a tradition at the institute, which earned the weekly lectures the intriguing name 'shotgun seminars'.[25] Each week, the department held a seminar, but instead of announcing the speaker well beforehand, the audience – and the speaker himself – only found out on the day. When the audience arrived, a hat was passed around and everyone took from it a piece of paper. Whoever picked the last piece of paper gave the seminar that day. The idea was to make sure everyone was on their toes: ready to give their own talk, but equally fired up to grill whoever took to the floor.

When the audience had exhausted its supply of questions, Dyson called a tea break and announced that their guest, Peter Higgs, was speaking next. Higgs followed the crowd out to the canteen and over a cup of tea fell into conversation with a German physicist called Klaus Hepp. The two had met once before at a summer school in Scotland in 1960. As the two sat chatting, Hepp mentioned a paper that was about to be published by three highly regarded scientists.[26] It was, he was sorry to say, a body blow for Higgs's theory. 'There's no doubt about it,' Hepp said, as the two made their way back to the lecture theatre. 'You've got something wrong.'

At least Oppenheimer wasn't around. Higgs had no idea, but the bullying director was gravely ill with cancer and was to formally step down three months later.[27] At the podium, Higgs collected his papers and, step by step, took the audience through his theory. Dyson listened intently. He thought Higgs's work was beautiful.[28] When their guest had finished speaking, several hands shot up around the room.

Although Higgs was anxious about the seminar, there was an underlying confidence in his manner. He knew the equations in his theory so well he could feel their deeper meaning. He was sure the ideas he put forward were sound. That didn't mean they were true, of course. Many things that are theoretically possible are not realised in nature. But if the theory was flawless, it was at least a contender for describing the origin of mass.

The questions from the audience were insightful, probing and critical, but none exposed any mistakes in Higgs's logic. His theory had passed its most challenging test yet. Dyson thanked Higgs for speaking and closed the session, delighted that the talk had gone well. Later, Higgs heard that Arthur Wightman, a leading physicist in the audience, had told his colleagues they had better go back and check their 'proof' that contradicted Higgs's theory. He had believed every word Higgs had said.

The next day after dinner with the Dysons, Higgs took to the road again. A second invitation had arrived from Harvard University, where Sidney Coleman, a prominent and playful physicist worked, and Higgs had agreed to drop in for an open discussion before heading back to Chapel Hill. The talk had been scheduled for the afternoon, which wasn't unexpected. Coleman famously missed morning appointments and once explained his failure to give a 9 a.m. lecture by protesting that he couldn't possibly stay up that late. Coleman was hoping to have some fun with Higgs.[29] He later confessed that he'd told his students some idiot was coming to see them. 'And you're going to tear him to shreds!'

The mauling never happened. At Harvard, Higgs's talk turned into an enthusiastic discussion that everyone joined in. Once more, the theory stood up to scrutiny. If the audience began with hopes of pulling it apart, they finished with a sense of intrigue. Higgs's theory was a watershed moment; one of those crucial steps that opens a door to a new world of physics where discoveries are there for the taking.

Science has a long history of squandering brilliant ideas.

They come at the wrong time, or they are clumsily explained, or they don't get noticed by the right people. Any one of these can relegate a profound leap in understanding to obscurity and deaden the progress of science. In a trip lasting less than a week, Higgs had made sure his theory didn't vanish without trace. Gradually, other physicists started trying to make sense of it. They started to talk of the Higgs mechanism, Higgs fields and the particle whose existence would prove it all to be real, the Higgs boson.

That autumn Higgs returned to Edinburgh and threw himself into his work with renewed vigour. An obvious question mark hung over his theory. Was it more than just a brilliant idea? Could it be a neat trick that nature had passed up on? He needed to take the idea and show how it worked in the real world. As it was, the theory was light on details. It showed how weightless particles *might* become massive in the early universe, but physicists had a whole zoo of particles to explain. Some of them had mass and others didn't. The theory didn't make clear which particles the Higgs field gave mass to and why.

The answer was destined to be one of the discoveries of the century. A handful of physicists who truly grasped Higgs's idea suspected it paved the way to what many consider the greatest goal in physics. Towards the end of his life, Einstein became obsessed with proving that the different forces of nature, such as electromagnetism and gravity, were originally part of one all-encompassing superforce that existed only fleetingly at the birth of the universe. Since that time, physicists have wondered if there might be a 'Grand Unified Theory', one that achieves Einstein's dream. Higgs's theory explained how nature could take all of the particles in the universe and at a stroke order some of them (the constituents of matter) to become heavy, while leaving others (like the photon) to remain massless. To physicists it seemed like a hint: that if they only dared to take Higgs's theory a little further, they might finally see how to reconcile all of nature's forces.

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