Educator's Guide and Script For
Atom: The Illusion of Reality

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INTRODUCTION

The goal of this program is to present an upper level high school or college introductory overview of the atom and show students how the vast variety and richness of everything we see around us is built up and how it fits together comes down to atoms and the mysterious laws they obey. In this program *Atom: The Illusion of Reality* Professor Jim Al-Khalili's explores how studying the atom forced us to rethink the nature of reality itself. He encounters ideas that seem like they're from science fiction but in fact are a central part of modern science. He discovers there might be parallel universes in which different versions of us exist and finds out that empty space isn't empty at all, but seething with activity. The world we think we know, the solid, re-assuring world of our senses, turns out to be a tiny sliver of an infinitely weirder and more wonderful universe than we had ever conceived of in our wildest fantasies.

ADVANCED VOCABULARY DEFINITIONS

- **Anderson, Carl - (**3 September 1905 - 11 January 1991) An American physicist, he is best known for his discovery of the positron in 1932, for which he received the 1936 Nobel Prize in Physics, and of the muon in 1936
- **Anti-electron** - The positron or anti-electron is the antiparticle or the anti-matter counterpart of the electron
- **Anti-neutron -** The anti-particle of the neutron
- **Anti-particle -** Corresponding to most kinds of particles, there is an associated anti-particle with the same mass and opposite electric charge. For example, the antiparticle of the electron is the positively charged anti-electron, or positron
- **Anti-proton -** The antiparticle of the proton
- **Bohr, Niels -** (7 October 1885 - 18 November 1962) A Danish physicist who made foundational contributions to understanding atomic structure and quantum mechanics, for which he received the Nobel Prize in physics in 1922
- **Cloud chamber -** The cloud chamber, also known as the Wilson Chamber, is used for detecting particles of ionizing radiation. In its most basic form, a cloud chamber is a sealed environment containing a super-cooled, supersaturated water or alcohol vapour. When an alpha particle or beta particle interacts with the mixture, it ionises it. The resulting ions act as condensation nuclei, around which

a mist will form (because the mixture is on the point of condensation). The high energies of alpha and beta particles mean that a trail is left, due to many ions being produced along the path of the charged particle. These tracks have distinctive shapes (for example, an alpha particle's track is broad and straight, while an electron's is thinner and shows more evidence of deflection). When a vertical magnetic field is applied, positively and negatively charged particles will curve in opposite directions

- **Cosmic rays -** Energetic particles originating from space that impinge on Earth's atmosphere
- **Curie, Marie -** (7 November 1867 - 4 July 1934) A physicist and chemist who was a pioneer in the field of radioactivity and the first person honored with two Nobel Prizes, in physics and chemistry
- **Dirac, Paul -** (8 August 1902 - 20 October 1984) A British theoretical physicist. Dirac made fundamental contributions to the early development of both quantum mechanics and quantum electrodynamics
- **Dirac equation -** In physics, the Dirac equation is a relativistic quantum mechanical wave equation formulated by British physicist Paul Dirac in 1928 and provides a description of elementary particles, such as electrons, consistent with both the principles of quantum mechanics and the theory of special relativity
- **E=MC2 -** Einstein's equation showing that Energy is equal to mass times the speed of light squared
- **Einstein, Albert - (**14 March 1879 - 18 April 1955) German Swiss Nobel Laureate who is often regarded as the father of modern physics.
- **Einstein's Special Theory of Relativity -** The theory proposed in 1905 by Einstein, which assumes that the laws of physics are equally valid in all non-accelerated frames of reference and that the speed of electromagnetic radiation in free space has the same value for all inertial observers. It leads to the idea of a space-time continuum and the equivalence of mass and energy. In combination with quantum mechanics it forms the basis of the theory of elementary particles. Also called special relativity
- **Electro-magnetic field -** A physical field produced by electrically charged objects. It affects the behavior of charged objects in the vicinity of the field
- **Feynman, Richard - (**11 May 1918 - 15 February 1988) An American physicist known for his work on the theory of quantum electrodynamics for which with Julian Schwinger and Sin-Itiro Tomonaga, he received the Nobel Prize in Physics in 1965
- **Gell-Mann, Murray -** (15 September 1929) An American physicist who received the 1969 Nobel Prize in physics for his work on the theory of elementary particles
- **Gravity** - The natural force of attraction exerted by a celestial body, such as Earth, upon objects at or near its surface, tending to draw them toward the center of the body
- **Hess, Victor -** (24 June 1883 - 17 December 1964) An Austrian-American physicist, and Nobel laureate in physics, who discovered cosmic rays
- **Kaon -** In particle physics, a kaon, also called a K-meson, is any one of a group of four mesons distinguished by the fact that they carry a quantum number called strangeness

- **Lamda -** An electrically neutral baryon particle
- **Magnetic moment -** The product of the pole strength of a magnet and the distance between the poles
- **Muon -** An elementary particle in the lepton family
- **Neutrino -** Any of three electrically neutral subatomic particles in the lepton family
- **Oppenheimer, Robert -** (22 April 1904 - 18 February 1967) American physicist who headed the Manhattan Project which developed the world's first Atom Bomb. He is also, known as the "Father of the Atomic Bomb"
- **Pion - S**hort for pi meson, it is the collective name for three subatomic particles
- **Positron -** A positively charged anti-electron
- **Quantum electrodynamics -** The quantum theory of the properties and behavior of muons, photons, and electrons and the electromagnetic field
- **Quantum foam -** A concept in quantum mechanics, devised by John Wheeler in 1955. The foam is supposedly the foundations of the fabric of the universe, but it can also be used as a qualitative description of subatomic space-time turbulence at extremely small distances
- **Quantum mechanics -** A branch of physics providing a mathematical description of much of the dual particle-like and wave-like behavior and interactions of energy and matter
- **Quarks -** A generic type of physical particle that forms one of the two basic constituents of matter
- **Rutherford, Ernest -** (30 August 1871 - 19 October 1937) a New Zealand chemist and physicist who became known as the father of nuclear physics
- **Schrodinger, Erwin** - (2 August 1887, Erdberg - 4 January 1961) An Austrian theoretical physicist who achieved fame for his contributions to quantum mechanics, especially the Schrödinger equation, for which he received the Nobel Prize in Physics in 1933
- **Schwinger, Julian - (**12 February 1918 - 16 July 1994) An American theoretical physicist best known for his work on the theory of quantum electrodynamics for which he won a Nobel Prize in Physics in 1968 with Richard Feynman and Sin-Itiro Tomonaga
- **String theories -** A mathematical theory for describing the properties of fundamental particles, which represents the particles as one-dimensional string-like objects, which exist in the normal four dimensions of space-time plus additional dimensions, the total dimensions being ten, eleven, or twenty-six depending on the version of the theory
- **Virtual particles -** A particle that exists for a limited time and space, introducing uncertainty in their energy and momentum due to the Heisenberg Uncertainty Principle

SCRIPT

ATOM: THE ILLUSION OF REALITY

Chapter 1: The Quantum Revolution Revisited

In 1912, in a hot air balloon about 3 miles above the ground, an Austrian scientist called Victor Hess made one of the most astonishing discoveries in science. Up here Hess found that incredibly mysterious rays of energy were pouring in from outer space and streaming through the earth. They were incredibly powerful and yet unlike anything anyone had ever seen before, they were called cosmic rays.

At the same time in laboratories down below, scientists were studying equally mysterious and equally powerful rays of energy pouring out of the deep interior of atoms - energy known as radioactivity. Mysterious rays from the vast emptiness of outer space, and mysterious rays from deep within the atom - the tiniest building block. No one understood what they were let alone believed that they might be connected. Then an incredible story unfolded. Cosmic rays and radioactivity turned out to be connected but in a way so shocking that it beggars belief.

The discovery of this connection would force us to rethink the nature of reality itself. The world we think we know, the solid, re-assuring world of our senses, turns out to be a tiny sliver of an infinitely weirder and more wonderful universe than we had ever conceived of in our wildest fantasies. Our reality is just an illusion.

In the years up to the mid-nineteen twenties, the atom revealed its strange secrets to us at a prodigious rate as it produced one scientific revolution after another. In 1897 Marie Curie studied strange rays pouring out of some rare metals. She called them radioactivity. Then in 1905 Albert Einstein conclusively proved the existence and size of an atom by studying the way pollen moves in water. A few years later the New Zealander Ernest Rutherford performed an experiment in Manchester that revealed to him the shape of the interior of an atom. Scientists were shocked to discover that the atom is almost entirely empty space.

The question then became how could this empty atom possibly make the solid world around us? The answer to that was worked out by a group of revolutionary physicists in Denmark. They proposed that the world of the atom ran on principles which were completely different to any mankind had ever seen before.

It meant that the atom, the basic building block of everything in the universe, was unique and perhaps outside human comprehension. Then, as scientists explored the nucleus, the tiny heart of the atom they found it bursting with powerful energy. This discovery gave them the potential to bring about the destruction of the earth, but in a shocking turnaround it also gave them a fundamental understanding of how the universe itself was created. And yet despite this, the journey to understand the strange and capricious atom had only just started.

Chapter 2: The Anti-Matter Universe

In 1927 a young man was studying at the Mathematics Department of Cambridge University. Shy, awkward, clumsy and frighteningly brilliant - his name was Paul Adrien Maurice Dirac. It’s probably fair to say that Paul Dirac isn’t a household name. But he should be. He was recently voted by other physicists as the second greatest English physicist of all time, second only to Isaac Newton. And he deserves the accolade. All the brilliant minds that pioneered atomic physics were left trailing by Dirac, aghast at the sheer boldness and lateral thinking in his work. When Einstein read a paper by the then 24 year old Dirac, he said, "I have trouble with Dirac. This balancing on the dizzying path between genius and madness is awful."

In 1927, for reasons no one has ever really fathomed, Paul Dirac set himself a task which was monumental in its scope - to unify science, to bring its scattered parts into one beautiful entity. And what this meant above all, was to unite the two most difficult and counter-intuitive ideas in history.

Here’s what Dirac was trying to reconcile. First there's quantum mechanics - a set of mathematical equations that describe the atom and its component parts. Then there's Einstein's Special Theory of Relativity - which at first glance seems completely unrelated to the atom. It deals with loftier matters like the nature of space and time themselves. One of its consequences is that objects behave very differently when they travel close to the speed of light.

The first thing you might ask is why would anyone want to reconcile two such different theories? Well, by late 1920's, the equations of quantum mechanics were getting consistently wrong answers when describing electrons - the constituents of atoms as they move at very high speeds.

But for Dirac there was a much more esoteric motivation. He was once quoted as saying, “A physical theory must have mathematical beauty.” To him, the fact that quantum mechanics and relativity weren't reconciled was not just inconvenient, it was downright ugly.

So around 1925 in Cambridge, Dirac put his extraordinary mind, a mind that even Einstein had trouble keeping up with, to work. This is room A4 New Court and it was Dirac’s original study. The original fireplace has been boarded up now, but it was here that Dirac tried to understand the two new ideas of 19th Century physics. And these are two quite different pictures of the universe. Word is that Dirac would sit here in front of his blazing fireplace and try to bring these two theories into one unified picture, one single equation.

For three frustrating years he labored alone on the problem. Then one evening in early 1928, he had an amazing revelation. The only way I can explain what happened is to say the equations of Quantum Mechanics and Special Relativity coalesced inside Dirac's mind. Einstein's description's of space and time somehow stretched and squeezed the existing equations of the atom. They bent and twisted them into all sorts of new weird and wonderful shapes. Then, guided by his unshakable belief that nature's laws must be beautiful, Dirac honed in one equation, an entirely new description of what goes on inside the atom.

Dirac knew it was right because it had mathematical beauty. Here it is, the Dirac Equation. Don't try and understand it. Just look at it and marvel. As far as human achievements go, it's up there with *King Lear,* Beethoven's *Fifth* or *The Origin of the Species*. Because hidden in these symbols is the perfect description of how reality works at a fundamental level, it is the key to nature's secret code.

With perfect mathematical elegance Dirac's equation describes an atomic particle travelling at any speed, right up to the speed of light. That much Dirac was expecting to achieve. But when he looked at his own equation more carefully, he noticed something breathtakingly revolutionary about it. He later said his equation knew more than he did.

In essence Dirac's equation was telling him that there is another universe that we've never noticed before. That's because instead of his equation having one answer, it has two. The first describes the universe we know, made of the atoms we're familiar with. The second describes a kind of mirror image to our universe, made of atoms whose properties are somehow reversed. Science fiction fans will know what's coming. As well as matter, Dirac's equation predicts the existence of 'anti-matter'.

Dirac's theory seemed to say that for everything in our known world, for every part of an atom, every particle there can exist a corresponding anti particle, with the same mass but exactly opposite in every other way. And just like a world in a mirror, a universe made of anti-matter atoms would look and work just like ours.

It would be perfectly possible for me to be made entirely out of anti-matter. The anti-me would look and behave exactly like the original me. And indeed, it is possible that out there in the vast expanse of the cosmos, there are stars and planets and even living beings, made out of anti-matter. And there's one final prediction from the Dirac equation. As its punch line, it states that matter and anti-matter must never come into contact because if they do they will annihilate each other in a fierce conflagration of pure energy. The combined mass of matter and the anti-matter would convert completely into energy according to Einstein's famous equation E=mc2.

So if I ever do meet my doppelganger, we would explode with an energy equivalent to a million of Hiroshima size atom bombs.

All this sounds like science fiction and indeed the idea of anti-matter has inspired huge swathes of it. But the truth is anti-matter, particularly anti-matter electrons, called 'positrons' are made routinely now in laboratories. Positrons are used in sophisticated medical imaging devices called PET scanners that can see through our skulls and accurately map pictures of our brains. But back in the 1920s the initial reaction to Dirac's equation among physicists was deeply skeptical.   Even Dirac himself had trouble believing his own results. Anti-matter seemed such a preposterous concept.

Chapter 3: The Theory of Nothing

Then came resounding confirmation of the Dirac equation and all its paradoxical implications. And it came from the most unexpected place - outer space.
In 1932 physicist Carl Anderson was working here at Caltech in Los Angeles, when he made an amazing discovery, he'd been studying cosmic rays. These are high-energy sub atomic particles that continuously bombard the earth from outer space.

To do this he used a device called a cloud chamber. This is basically a vessel that's filled with a fine mist of water vapor. This shows the track of the particles as they stream down through the vapor. And placed inside a magnetic field these tracks would be deflected one way or the other depending on the electric charge of the particle. So positive particles tracks bend one way and negative the other. Anderson found evidence of particles, which look exactly like electrons but are deflected in the opposite direction. He had discovered Dirac's anti-electrons, particles of anti-matter.

The Dirac equation is an impressive achievement. Its prediction of the existence of anti-matter using abstract mathematics alone would be enough to make it a significant milestone in the history of human thought.

But within just a few years of its publication, first Dirac and then others, sensed that his new equation was telling them something profound, something completely new about nature. They were right. But the revelation hidden in Dirac's equation would take the best efforts of the greatest minds 30 years to uncover.

The problem with Dirac's Equation was this. Although it was incredibly powerful and had lead to the discovery of anti-matter, ultimately it could only describe a single electron. It fails completely to explain what happens when there is more than one electrons present.

What was needed was a new theory, a theory which explains how electrons interact with each other. And that turned out to be the most difficult question of the mid twentieth century. But when an answer came, it was to bring with it an unexpected revelation.

This office in Caltech just outside Los Angeles used to belong to the great Richard Feynman. In our story of so many geniuses of science, Feynman stands, in my view, second only to Einstein in the list of the greatest 20th century physicists. You see Feynman wasn't just a common or garden genius, many referred to him as a magician, he was so smart, such an innovative thinker. And like Einstein he became this mythical figure. Certainly a household name. Feynman was a larger than life character, he had a huge personality. He loved cultivating and telling anecdotes about himself. He used to frequent strip clubs; he had affairs with his students; he was even rumored to go to orgies.

But his greatest contribution to physics was the part he played in developing the next phase of quantum mechanics. Feynman and his contemporaries were attempting to pick up the atomic torch from Paul Dirac and develop a theory that took our understanding of the atom literally a quantum leap further. Like Dirac's anti-matter equation before, the intention of the new theory was unification. They wanted to understand how electrons affect each other. In other words it aimed to explain how everything works together through the electromagnetic field. They called their unification project Quantum Electrodynamics, or QED.

The Project was a formidable challenge but the end result was magnificent. Nothing less than the most far reaching accurate scientific theory ever conceived.

For instance it predicts a certain property of the electron called its magnetic moment to have a value of 2.002319304. Experiments measured precisely the same number. That's an agreement between theory and experiment to one part in ten billion. It's an unprecedented level of agreement. It's like measuring the distance between London and New York to within the thickness of a human hair.

The phenomenal accuracy of Quantum Electro Dynamics shows it to underpin almost everything we experience in the physical world. It's as close to a theory of everything as we've ever come.

It defines the laws of nature, the atomic scale. It explains, shape, color, texture and the way almost everything interacts and fits together. It underpins and encompasses everything from the biochemistry of life to why we don't fall through the floor.
So what does QED actually say? Well, this is where the going gets very tough.
It may be a wonderful scientific description of nature but trying to understand what Richard Feynman was doing with his theory is almost impossible. This is what he himself said when he introduced his theory to the public: "It is my task to convince you not to turn away because you don't understand it. You see my physics students don't understand it. That is because I don't understand it. Nobody does."

If the inventor of the theory doesn't understand, what possible hope is there for the rest of us? With that disclaimer I'm going to try and explain anyway. First abandon your most basic intuition about nature - you have to give up the notion that empty space is empty. Let me try and explain. If I were to sap out all the air from this jar, you'd quite likely say that having removed all the atoms, I am left with a vacuum, a volume of pure emptiness.

Quantum Electrodynamics flies in the face of this common sense idea by saying that the vacuum is not, I repeat not, a place where nothing exists and nothing happens. Instead it's full of 'stuff' and is heaving with activity. How can this possibly be true?

Well - let's imagine one tiny point in the emptiness. Common sense tells us there's nothing there. But quantum physics tells us, that there's only nothing there on average. And it's those two words 'on average' that force us to rethink our understanding of reality.

Think of empty space as a bank account which on average has nothing in it - as a physics academic, this is a concept I am familiar with. Some days it might be a hundred pounds in credit, other days it could be a hundred pounds overdrawn - on average there's a zero balance. Empty space turns out to have similar accounting skills but it can borrow energy rather than money. And this energy is literally borrowed from the future provided that its paid back again very quickly.

In practice what this means is that the borrowed energy which are spontaneously formed from the void provided that a fraction of a second later they annihilate each other and disappear. Energy is borrowed out of nowhere, it's turned into matter. The matter then self-destructs back into energy; and this in an instant all over the void. In fact in a stunning confirmation of Dirac's anti-matter theory the vacuum seethes with huge numbers of matter and anti-matter particles continually being created and annihilated. Down at the smaller scale space is a constant storm of creation and destruction. Physicists call it the 'quantum foam'.

Chapter 4: Quantum Electrodynamics

The particles in the quantum foam come and go so quickly that we're completely unaware of them. We refer to them as 'virtual particles'. But if we were able to slow time down almost to a standstill, we'd be able to see this seething activity, this constant creation and annihilation of matter and energy that's the fabric of reality itself. And from this comes the most jaw-dropping idea of all. Quantum Electrodynamics says that the matter we think of as the stuff that makes up the real world, the world we see and feel is a kind of left-over from all the feverish activity that virtual particles get up to in the void. So you, me, the Earth, the stars - are basically just a part of a deeper, infinitely more complex reality than we ever imagined.

Of course, when Feynman first started to develop his revolutionary ideas at Caltech in the mid forties, his contemporaries were horrified. Because at that time the general opinion was that the Quantum Electrodynamics project was an unmitigated disaster. The theory couldn't be solved; the equations had no sensible solutions; the mathematics had spiraled out of control.

But Feynman believed that he could see a way through the mathematical complexity to a new truth. What Feynman did with all the arrogance and confidence of youth was slash through the insanely complicated maths. Feynman developed a new series of revolutionary but almost childlike diagrams to explain his new ideas. Their elegant simplicity flew in the face of the complex maths of traditional quantum mechanics. Conflict seemed inevitable. Then in 1948, at the age of 30, Richard Feynman decided to unveil his controversial version of Quantum Electrodynamics, with his idiosyncratic diagrams to the physics world. And he chose the most important science conference of the American calendar.

Set on the coast of Pennsylvania, the Shelter Island conference was a monster physics celebrity circus. Present were Niels Bohr, the so-called father of atomic physics, the discoverer of anti-matter, Paul Dirac, and the man behind America's Atom Bomb, Robert Oppenheimer. The atmosphere at the start of the conference was grim. Confidence in Quantum Electrodynamics was at rock bottom. It seemed a hopeless mess. One after another the physicists droned on despairingly about how they had failed to find a solution.

Then it was the turn of Richard Feynman. Barely 30 years old he stood up and took his place in front of the world's most illustrious scientists and started to unveil his new diagrams and equations. What happened next was astonishing. A row broke out, not so much over Feynman's weird description of reality - physicists were used to weird by now - but because he dared to visualize what was going. Instead of using arcane complicated mathematics, Feynman was describing what all his virtual particles were up to using his simple pictures. There was uproar. Niels Bohr, the father Quantum Mechanics, leapt out of his chair disgusted.

He hated Feynman's diagrams because they went completely against what he had devoted his whole life to. You see he believed that atomic particles could not be visualized under any circumstances.

Feynman defended his new theory, trying to explain that the diagrams were simply a tool to visualize his new equations, but the rest of the scientists including Paul Dirac wouldn't hear it. They called him an idiot who understood nothing about quantum mechanics. Feynman ended his lecture bruised but unrepentant. He knew that his new diagrams and equations were correct, if only he could convince the others.

That evening Feynman met another young physicist called Julian Schwinger. Now Schwinger was the same age of Feynman and was considered a child prodigy at the age of 12. He and Feynman had been working independently and had approached the problem of quantum mechanics very differently. They'd reached identical conclusions.

With their new equations they could solve QED. And with Feynman's diagrams they produced a theory of awesome power. Together now as allies they planned a full frontal attack on Niels Bohr and the conservatives. By the end of the conference the mood in the Pennsylvanian conference had changed from one of frustrated hopelessness, to one of excitement and idealism.

Over the next few years, their theory was fleshed out and rapidly became the most accurate and powerful theory mankind had ever had. Despite finally being tamed, QED's, talk of empty space seething with energy we can't feel and virtual particles that we can't see does make many people, including physicists, a little suspicious. And many skeptics might say these ghostly objects that allegedly fill the vacuum aren't actually real. Yes, the complicated mathematical equations of Quantum Electrodynamics seem to require them but that doesn't itself mean they exist. They might just be mathematical fantasies with no basis in reality.

Well, I have bad news for the skeptics. Since the late 1950's, direct evidence that empty space is not in the slightest bit empty, but is in fact seething with activity, has been observed time and time again in laboratories. Quantum Electrodynamics is by any measure a truly magnificent discovery.

Chapter 5: Sub-Atomic Particles

It's one great pinnacle of our story - a glorious conclusion to five amazing decades of science. In Quantum Electrodynamics, the atom had given us a theory that explains much of our universe with stunning accuracy. But since Quantum Electrodynamics' triumphant arrival in the late 40's our story becomes rather messy and awkward. As a result of Quantum Electrodynamics, scientists were convinced that everything in the universe consisted of essentially just two things - atoms and light. Light was made out of tiny particles called photons, and atoms were made out of three components, the electron, the proton and the neutron. And because of anti-matter there were anti-protons, anti-neutrons and positrons - a bit strange but pleasingly symmetrical.

Everything in the physics garden was rosy thanks to the rules of Quantum Electrodynamics. But then, much to the profound irritation of every working physicist, a load of new and exotic particles suddenly appeared like party gate crashers to spoil the fun. Exotic entities that didn't fit into any known theories were appearing in physics labs with such frequency that scientists couldn't keep up with naming them all - the neutrino, the positive pion, the negative pion, the kaon, the lamda, the delta and of course each of these had anti-matter counterparts. When one new particle, named a muon was discovered, one physicist quipped, "Who ordered that?"

The whole thing was a mess that didn't make sense - and physicists despairingly referred to it as the 'particle zoo.' It began to seem as though every time scientists solved one of nature's mysteries, the atom would present them with something even more weird. Within just a few years atomic physics had gone from a position of quiet confidence to total chaos. And of course, to make some sense of this new mystery would require, yes you've guessed it, another scientific revolution.

The third genius in our story is Murray Gell-Mann. Gell-Mann was a child prodigy, by the age of 15 he'd already started at Yale to study physics, and had finished his PhD by the time he was in his early 20s. He had an incredible intelligence, which terrified those around him. He spoke many languages and seemed to have a deep knowledge of any subject you cared to throw at him. Like Richard Feynman, whom he joined here at Caltech in the early 60s, he seemed to have the ability to see beyond the mathematics and the formalism of his theories to the underlying secrets of nature below.

Together Gell-Mann and Feynman made an awesome duo. This is office number 456 which used to belong to Feynman. What's great is that just two doors along the corridor is the office of Murray Gell-Mann. There was an intense academic rivalry between these two intellectual giants. But they fed off each other's creativity. There were very different personalities - Feynman who played the buffoon, Gell-Mann the cultured elitist.

Gell-Mann used to get upset by Feynman's loud voice and Feynman enjoyed winding him up. But it's fair to say that during the 60s and 70s these two geniuses at Caltech dominated the world of particle physics.

Their bitter rivalry pushed them both to the very limits of their imaginations. And Gell-Mann especially was desperate to prove himself over Feynman by bringing some order into the particle zoo. Within the feverishly intellectual atmosphere of Caltech, Gell-Mann's mind did something very strange. He started working with a different kind of mathematics to deal with the preponderance of subatomic particles. He used an obscure form of maths called Group Theory.

As its name suggests this is a theory that analyses groups of numbers and symbols and tries to organize them into simple patterns and symmetries. It a bit like working with an abstract form of origami. Using a technique Gell-Mann started working all known particles into an organized system which he called the Eight Fold Way, after a Buddhist poem. But then he had his most awesome revelation. Gell-Mann realized that his Group Theory pointed towards a new deeper underlying mathematical truth, something which has the potential of re-writing the atomic rule book. What Gell-Mann's mathematics revealed to him was that in order to make coherent patterns of the all the new particles in his Eight Fold Way, he had to acknowledge that there was a deeper, underlying fundamental reality.

Once again, it turned out that things were not at all what they seemed. You see physicists have been comfortable with the notion that atoms are made of three different kinds of particles. Electrons orbited around the nucleus itself made up of protons and neutrons. Gell-Mann had the temerity to suggest that protons and neutrons were themselves composed of more elementary particles, particles that he called quarks.

Chapter 6: Quarks

Murray Gell-Mann was cultured and arrogant, but at heart lacked confidence. He knew that for his colleagues, even those used to the strangeness of the atom quarks were a step too far. And in any case there'd been any evidence of anything remotely like a quark. He was convinced his new theory would be declared outlandish or just wrong. So Gell-Mann sat on his revelation. And one of the greatest ideas in science was almost lost forever. Then something extraordinary turned up just a few hundred miles north of his office.

This is the Stanford Linear Accelerator a few miles south of San Francisco. What you can see below me is one end of what is basically a giant electron gun. A beam of high-energy electrons is fired through a tunnel that starts off over two miles away in the hills. And travels underneath the freeway and comes out at this end where it enters the experimental area. The Grey building there is called End Station A and it's where one of the most important discoveries in physics was made.

It was built during the 1960s when it was and still is today the longest single building on earth. And although it's 40 years old, you can see a lot of construction work going on now, it's still being used for fundamental research today. I'm now inside the 2-mile long linear accelerator building. The red objects you see on your right are called Klystrons and they provide the boost, which moves the electron beam, which runs 20 feet below us. Such is the acceleration that these electrons will within the first few meters have reached 99% of the speed of light.

Let me put this another way. If these electrons were to start off their journey at same time that you fire a bullet from a gun, they would have covered the full 2 miles distance before the bullet had even left the barrel. The electron beam now travelling at almost the speed of light would arrive here at the target area. There would have been in 1968, where I'm standing now, a large tank of hydrogen - basically protons. The electrons would smash into the protons and scatter off through tubes to be picked up by huge detectors that filled the hall outside. And as they did this, physicists got their biggest ever confirmation that there might be deeper set of rules underpinning the particle zoo. What they discovered, from the way the electrons scattered and because of their extremely high energy was conclusive proof that protons have internal structure. In other worlds, protons were themselves made of more elementary particles. Here were Gellman's quarks.

This was an astonishing moment. For decades people were confident that the components of the atomic nucleus, the proton and the neutron, were absolutely fundamental. And now for the first time there was evidence of something deeper.

The quark is a tricky and elusive beast. There are six different kinds or flavors of quark; up, down, strange, charm, top and bottom. Also quarks never exist in isolation, only in combination with other quarks - this makes them impossible to see directly. We can only infer their presence. But despite these caveats, the quark brought some semblance of order to the particle zoo. In recent years, it's allowed us to concoct a simple yet powerful description of how the universe is built up.

Basically everything in the universe made of atoms is built up from just quarks and electrons, that's it. This now brings us pretty well right up to date. The discovery of the quark in 1967 was the last significant experimental discovery of a new type of fundamental particle. Some say we may yet discover the quark is made of something even stranger. And it's possible. But for now it's as good as it gets.

Our journey from Einstein's proof of the existence of atoms 1905 until now has been extraordinary. We've learnt so much about the atomic world, from the size and shape of the atom, to how its centre holds the secret of the universe itself. From how it reveals an unknown world of anti-matter, to how empty space is far from empty. From what we thought was a basic building block of the universe itself to the discovery of something even more fundamental inside it.

Chapter 7: The Atom's Paradoxes

And yet, despite all the powerful science, which we have uncovered, something doesn't quite add up. There are two startling and worrying anomalies. The first of these is now at the forefront of theoretical physics across the world. And it concerns one of the oldest scientific principles there is - gravity.

Now, though gravity has been very thoroughly understood since Einstein it has never really been a part of atomic theory until now, suddenly there's a glimmer of hope from ideas that sound almost too crazy to be possible. Some of these are called String Theories that regard all sub atomic particles as tiny vibrating strings that have higher dimensions of space trapped within them. Some called Brane Theories suggest our entire space and time is just a membrane floating through the multi-verse. Another called quantum loop gravity suggests that nothing really exists at all and that everything is ultimately made up of tiny loops in space and time themselves.

But despite gravity's unwillingness to fit in with quantum theory, I believe there's something worse lurking in the quantum shadows, something truly nightmarish.
Late into the night at physics conferences all over the world, over drinks at the bar where we scientists huddle together to debate and discuss our strangest ideas and dreams, there are still things that really really bother us. And chief among these are the quantum mechanical laws that atoms obey and in particular one aspect of those laws, something called 'the measurement problem'. If you want to see fear in a quantum physicist's eyes, just mention the words 'the measurement problem'.

The measurement problem is this: an atom only appears in a particular place if you measure it. In other words, an atom is spread out all over the place, until a conscious observer decides to look at it. So the act of measurement or observation creates the universe. To show just how mad this idea is, I'm going to explain the most famous hypothetical experiments in the whole of science. It's called the Schrodinger's Cat experiment.

Erwin Schrodinger was one of the founding fathers of atomic theory and in the mid 1930s devised a thought experiment purely to highlight the absurdity of quantum mechanics. He suggested you take a box in which you place an unopened container of cyanide connected to a radiation detector and some radioactive material. Now the idea is that if an atom in the material emits a particle this'll be picked up by the detector which in turn releases the cyanide. Next you take Schrodinger's cat. Which in this case is a lovely Norwegian Forest Cat called Dawkins. Now I should point out that this isn't real cyanide. You place the cat in the box, you close the lid and wait.

So here's the conundrum. According to traditional quantum mechanics, known as the Copenhagen Interpretation, all the time the box is closed the radioactive atom inside has yet to make up its mind whether it has decayed and spat out a particle. So we have to describe it as both having decayed and not decayed at the same time.

Think about what that means. Since the radioactive particle triggers the release of the poison, the cat is both poisoned and not poisoned. So until we open up the lid to check up on the fate of the cat - what's called making a measurement - it's not just that we don't know, but that the cat is both dead and alive at the same time. That is clearly paradox. Or is it?

The paradox of Schrodinger's Cat and the contradictory nature of their measurement problem really do force us to accept that tiny objects down at the atomic scale obey their own set of profoundly strange rules. But at larger scales, those of everyday human experience, those rules vanish and an utterly new set of nice, intuitive, rules takes over. How can this be?

Some argue that in fact the quantum weirdness of the atom might actually be writ large across the cosmos, that we may have to rethink everything we knew about the universe.

In the last one hundred years we have peered deep inside the atom, the basic building block of the universe. And inside this tiny object, we found a strange new world, governed by exotic laws that at times seem to defy reason. Atoms present us with dizzying contradictions. They can behave like particles and waves; they appear to be in more than one place at the same time, they force us to rethink what we mean by past and future, by cause and effect and tell us strange things about where the universe came from and where it is going - pretty amazing stuff for something that's just a millionth of a millimeter across. That's why Niels Bohr, the father of atomic physics, once said that when it comes to atoms, language can only be used as poetry.

But what is fascinating though, for me, is that although we know an incredible amount about atoms and their behavior, our scientific journey has only just begun. Because although we know how a single atom or just a few atoms behave, the way trillions of them come together in concert to create the world around us is still largely a mystery. To give you one dramatic example: The atoms that make up my body are identical to the atoms in rocks, trees and in the air even the stars. And yet they come together to create a conscious being, who can ask the question, 'What is an atom?' Explaining all that is surely the next great challenge in science.

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