Educator's Guide and Script For *Atom: Clash of Titans*

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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: Clash of Titans* nuclear physicist and host, Professor Jim Al-Khalili, tells the story of the greatest scientific discovery ever - the discovery that everything is made of atoms. As scientists delved deep into the atom, into the very heart of matter, they unraveled nature's most shocking secrets. They had to abandon everything they believed in and create a whole new science, which today underpins the whole of physics, chemistry, biology and maybe even life itself. 'Atom' tells a story of great geniuses, people like Albert Einstein and Werner Heisenberg who were driven by their thirst for knowledge and glory. It's a story of false starts and conflicts, ambition and revelation, a story which leads us through some of the most exciting and exhilarating ideas ever conceived of by the human race.

ADVANCED VOCABULARY DEFINITIONS

- **Alpha rays -** Rays of relatively low penetrating power emitted by radium and other radioactive substances, and shown to consist of positively charged alpha particles
- **Atom -** The atom is a basic unit of matter that consists of a dense, central nucleus surrounded by a cloud of negatively charged electrons. The atomic nucleus contains a mix of positively charged protons and electrically neutral neutrons
- **Bohr, Niels -** (7 October 1885 -18 November 1962) was 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
- **Boltzmann, Ludwig -** (February 20, 1844 -September 5, 1906) an Austrian physicist was one of the most important advocates for atomic theory when that scientific model was still highly controversial
- **Born, Max -** (11 December 1882 -5 January 1970) was a German born physicist and mathematician who was instrumental in the development of quantum mechanics

- **Brown, Robert –** (21 December 1773 -10 June 1858) a Scottish botanist who made important contributions to botany largely through his pioneering use of the microscope and was the discoverer of Brownian Motion..
- **Brownian motion -** Named for the Scottish botanist Robert Brown, it is the random movement of microscopic particles suspended in a liquid or gas, caused by collisions with molecules of the surrounding medium. Also called Brownian movement
- **Copenhagen Interpretation -** The interpretation of quantum mechanics developed by Niels Bohr and his colleagues at the University of Copenhagen, based on the concept of wave-particle duality and the idea that the observation influences the result of an experiment
- **de Broglie, Louis-Victor-Pierre-Raymond, 7th duc -** (15 August 1892 -19 March 1987) was a French physicist and a Nobel laureate
- **Einstein, Albert -** (14 March 1879 -18 April 1955) German swiss Nobel Laureate who is often regarded as the father of modern physics.
- **Electron -** A sub atomic particle carrying a negative electric charge
- **Geiger, Hans -** (September 30, 1882 -September 24, 1945) was a German physicist. He is perhaps best known as the co-inventor of the Geiger counter and for the Geiger-Marsden experiment which discovered the Atomic nucleus
- **Geiger counter -** A type of particle detector that measures ionizing radiation. It is notable for being used to detect whether objects emit nuclear radiation
- **Heisenberg, Werner -** (5 December 1901 -1 February 1976) was a German theoretical physicist who made foundational contributions to quantum mechanics and is best known for asserting the uncertainty principle of quantum theory
- **Heisenberg's Uncertainty Principle -** In quantum mechanics, the Heisenberg uncertainty principle states that the more you know the position of a particle, the less you can know about its velocity, and the more you know about the velocity of a particle, the less you can know about its instantaneous position
- **Matrix Mechanics -** Matrix mechanics is a formulation of quantum mechanics created by Werner Heisenberg, Max Born, and Pascual Jordan in 1925. It was the first complete and correct definition of quantum mechanics, by describing how quantum jumps occur. It did so by interpreting the physical properties of particles as matrices that evolve in time
- **Nucleus** -The very dense region at the center of an atom consisting of protons and neutrons
- **Pauli, Wolfgang -** (April 25, 1900 -December 15, 1958) An Austrian theoretical physicist and one of the pioneers of quantum physics
- **Quantum jump -** Abrupt change from one energy level to another, especially such a change in the orbit of an electron with the loss or gain of a quantum of energy
- **Quantum mechanics** - (QM), also known as quantum physics or quantum theory, is 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
- **Radioactivity -** The emission of ionizing particles or radiation from an unstable atomic nucleus

- **Radium -** A radioactive chemical element which has the symbol Ra and atomic number 88. Its appearance is almost pure white, but it readily oxidizes on exposure to air, turning black
- **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, Vienna) was 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
- **Schrodinger's wave equation -** An equation that describes how the quantum state of a physical system changes in time. It is as central to quantum mechanics as Newton's laws are to classical mechanics
- **Uranium -** a silvery-white metallic chemical element in the actinide series of the periodic table with atomic number 92
- **X-rays -** A form of electro-magnetic radiation

SCRIPT

ATOM: CLASH OF TITANS

Chapter 1: The Grand Search for the Secrets of Matter

This is the story of the greatest scientific discovery ever - the discovery that everything is made of atoms; the vast variety and richness of everything we see around us in the world and beyond; how it is built up and how it fits together is all down to atoms and the mysterious laws they obey.

As scientists delved deep into the atom into the very heart of matter, they unraveled nature’s most shocking secrets. They had to abandon everything they believed in and create a whole new science, a science that today underpins the whole if physics and chemistry and biology and maybe even life itself. But for me the story of how humanity solved the mystery of the atom is both inspiring and remarkable. It's a story of great geniuses of men and women driven by their thirst for knowledge and glory. It's a story of false starts and conflicts, of ambition and revelation, a story which leads us through some of the most exciting and exhilarating ideas ever conceived of by the human race. And for a working physicist like me it's the most important story there is.

On October the 5th 1906 in a hotel room near Trieste, a German scientist called Ludwig Boltzmann hanged himself. Boltzmann had a long history of psychological problems and one of the key factors in his depression was that he had been vilified, even ostracized for believing something that today we take for granted - he believed that matter cannot be infinitely divisible into ever smaller pieces. Instead he argued that ultimately everything is made of basic building blocks - atoms.

It seems incredible now that Boltzmann’s revelation was so controversial, but 100 years ago arguing atoms were real was considered by most to be a waste of time. Although philosophers since the Greeks had speculated that the world might be made out of some kind of basic unit of matter, they realized they were far too small to see even under the most powerful microscopes. Speculating about them was therefore a complete waste of time. But then in the middle of the 19th century, the existence of the atom became a question of burning importance. The reason was this - steam.

In the 1850's it was changing the world. It powered the mighty engines, the trains, the ships and factories of the industrial revolution. So figuring out how to use it more effectively was a matter of crucial commercial, political and military significance. Not surprisingly, it became the key question of 19th century science. The demand to build more powerful and efficient steam engines in turn created an urgent need to understand and predict the behavior of water and steam at high temperatures and pressures.

Ludwig Boltzmann and his scientific allies showed that if you imagine steam is made of millions of tiny rigid spheres, atoms, then you can create some powerful mathematical equations. And those equations are capable of predicting the behavior of steam with incredible accuracy. But these same equations plunged Boltzmann and his fellow 'atomists' into controversy. Their enemies argued that since the 'atoms' referred to in calculations were invisible; they were merely a mathematical convenience rather than real objects. To claim these imaginary entities were real seemed presumptuous, even blasphemous. Boltzmann's critics argued it was sacrilegious to reduce God's miraculous creation to a series of collisions between tiny, inanimate spheres. Boltzmann was condemned as an irreligious materialist.

The tragic irony of Boltzmann's story is that when he took his own life in 1906, he was unaware that he'd been vindicated. The year before he died, a young scientist had published a paper which undeniably, irrefutably proclaimed the reality of the atom. You might have heard of this young scientist - his name was Albert Einstein.

In 1905, the year before Boltzmann's suicide, Albert Einstein was 26 years old. His brash arrogance had upset most of his professors and teachers and he was barely employable. Then he got his girlfriend pregnant. That was followed by a hasty marriage. He needed a job, any job. Having not quite distinguished himself at university, he took up a job as a patents clerk here in Bern in Switzerland. He moved into this small, one bedroom apartment in Gramgasse with his young wife, Mileva.

Despite dire personal straits, the young Einstein had a burning ambition. He was desperate to make his mark as a physicist. And in 1905 during one miraculous year, the mark he made was truly incredible. Having an undemanding job meant that young Einstein had a lot of time on his hand at work and here at this tiny apartment to think deep thoughts.

In the space of just a few months he was to publish several papers that would change science forever. Now everyone has heard of his theory of relativity even if they don't understand it, and his paper on the nature of light was to win him the Nobel Prize a few years later. But ironically it wasn't either of these two papers that had the most impact on the discovery of atoms. The one that made all the difference was a short paper on how tiny grains of pollen danced in water.

Almost 80 years earlier, in 1827, a Scottish botanist called Robert Brown sprinkled pollen grains in some water and examined them through a microscope. What he found was really strange because instead of the pollen grains floating gently in the water they danced around furiously - almost as though they were alive. Now while this so-called Brownian motion was strange, scientists soon forgot about it. They found it mundane, even boring. Who cared if pollen jiggled about in the water? And what had the jiggling to do with atoms anyway?

For nearly 80 years Brown's discovery remained a little known scientific anomaly. Then Einstein changed everything. In one staggering insight, Einstein saw that Brownian motion was all about atoms. In fact he realized the jiggling of pollen grains in water could settle the raging debate about the reality of atoms forever. His argument was simple. The pollen will only jiggle if they were being jostled by something else. So Einstein said that the water must be made of tiny atom-like particles which themselves are jiggling and are continually buffeting the pollen. If there were no atoms, then the pollen would stay still.

So Boltzmann and his contemporaries had been rowing furiously about this question for nothing. The answer was there all along. Einstein proved that for Brownian motion to happen, atoms must exist. And Einstein's paper went way beyond just verbal arguments. With flawless mathematics, he proved that the dance of the pollen revealed the size of atom. It's mind-numbingly tiny. One tenth of a millionth of one millimeter across. It's hard to imagine something so tiny. A single human hair, itself one of the narrowest things visible to the naked eye, is over a million atoms wide. Let me put it another way, there are more atoms in a single glass of water than there are glasses of water in all of the oceans of the world. It sort of hurts your head just to think about it. Einstein's paper ended the debate about whether the atom was real or not. And Boltzmann had been totally vindicated. The atom had to be real.

Chapter 2: The Atom Has Structure

By the early years of the 20th century, the atom had arrived. Scientists who had argued that the atom was real were no longer heretics. In a dramatic, sudden reversal, they became the new orthodoxy. But they were to pay a huge price for their success. Before they'd even had a chance to congratulate each other on discovering the atom, it ripped the rug out from under their feet and sent them spiraling into a bizarre, and at times, terrifying new world.

And it all kicked off here in what by 1910 was the world centre for atomic physics - Manchester. Two of the most extraordinary men in the history science worked together here in the Manchester University Physics Department between 1911 and 1916. They were Ernest Rutherford and Niels Bohr.

Rutherford and Bohr were, on the face of it, very different men - the unlikeliest of collaborators. Rutherford was from a remote part of New Zealand and grew up on a farm. Bohr was born in Copenhagen, wealthy and erudite, virtually an aristocrat. Rutherford was the ultimate experimentalist. He loved technology and ingenious arrangements of batteries, coils, magnets and radioactive rocks. But he was also blessed with a profound intuition. In contrast, Bohr was the ultimate theoretician. To him science was about deep thought and abstract mathematics. Pen and paper, chalk and blackboard were his tools. Logic was his path to truth.

Although their approaches to their work couldn't have been any more different, they had one thing in common. They were prepared to ditch three centuries of scientific convention if it didn't fit what they believed to be true. They were genuine revolutionaries. Rutherford and Bohr were two of the most extraordinary minds ever produced by the human race. But it would take every bit of their dogged tenacity and inspirational brilliance to take on the atom.

In 1907 Ernest Rutherford took over the physics department in Manchester. This was a period of momentous scientific change. Just over ten years earlier in Germany came the first demonstration of weird rays that see through flesh to reveal our bones. These rays were so inexplicable scientists didn't know what to call them. So they were named X-Rays. And a couple of years after that in Cambridge, it was shown that powerful electric currents could produce strange streams of tiny glowing charged particles that were called electrons. And in 1896 in Paris, came the most significant discovery of all - one that more than any other would unlock the secrets of the atom. The metal uranium was shown to emit a strange and powerful energy that was named 'radioactivity.'

It seemed straight out of science fiction. Radioactive metals were warm to the touch, they could even burn the skin, and the rays could pass through solid matter as if it wasn't there. It truly was a marvel of the modern age.

Rutherford was obsessed with radioactivity. All sorts of questions plagued him. How was it made? Why did it come in different forms? How far did it travel through a vacuum or through air? Did it alter the materials it encountered? In Manchester, with his assistants Hans Geiger, of Geiger counter fame, and Ernest Marsden, Rutherford devised a series of experiments that would probe the enigma of radioactivity.

1909 ... Manchester University … These are the props: gold leaf beaten till it's just a few atoms thick; a moveable phosphorescent screen that flashed when struck by radioactive rays; and inside this box is the star attraction - a tiny piece of the metal radium. Radium is an extraordinarily powerful source of a kind of radioactivity that Rutherford had named alpha rays. They weren't really rays, they were more like a steady stream of particles, and radium spat out these particles like a machine gun that never ran out of bullets.

Rutherford set his students a simple enough task. Use the radium gun, shoot the alpha radioactivity at the gold leaf, and with the phosphorescent plate count the number of particles that come out the other side. In practice that meant sitting alone in the dark and counting tiny almost invisible flashes on the phosphorescent screen. It was deeply tedious but Rutherford insisted that they keep at it. Weeks passed and the team of researchers found nothing unusual. The alpha particles seemed to punch through the gold almost as if it wasn't there. Very occasionally they would swerve slightly as they went through the gold - hardly front page news.

Now comes what must be the most consequential off-the-cuff remark in history of science - one that changed the world. The story goes that Rutherford bumped into his assistant, Geiger, in the corridor outside the lab. Geiger reported that so far they'd seen nothing unusual. In response Rutherford could so easily have nodded and walked on but he didn't. Later he claimed he said what he said at that moment, "for the sheer the hell of it." But I don't believe him. Rutherford had great scientific intuition. I think he had a hunch that something was about to happen. Here's what he said to Geiger: "Tell young Marsden to go back and see if he can detect any alpha particles on the same side of the gold leaf as the radium source." In other words, see if any of the alpha particles are bouncing back.

It's an extraordinary suggestion from Rutherford and one that he had no logical reason to make. After all, Geiger and Marsden had spent weeks seeing the alpha particles do nothing but stream through the gold almost as if it wasn't there. Why would any bounce back? But Marsden and Geiger were young and in awe of the Big New Zealander. They did their master's bidding and went back into their dark lab and patiently watched.

For days, they saw absolutely nothing. They strained their eyes to the point of myopia, but didn't see a single alpha particle bounce back off the gold. It seemed Rutherford's suggestion really was a stupid one. But then the impossible happened.

One afternoon in 1909, Geiger burst into Rutherford's office with astonishing news. Very, very occasionally an alpha particle would indeed ricochet back off the gold leaf. Geiger calculated that only one in 8000 alpha particles would do this. It was tiny percentage but Rutherford's mind reeled with the news. He would later say it was like firing a shell at a piece of tissue paper and have it bounce back at you.

There and then, Rutherford knew he'd struck physics gold. Although it would take him a year to fully understand why alpha particles would do this, when he did he would show humanity for the first time the inside of an atom. Now, people had barely got used to the idea that atoms existed and now Rutherford knew this minute world, less than a ten millionth of a millimeter across, had its own internal structure. Within the atomic, there is a sub-atomic world. And Ernest Rutherford believed he knew what it looked like.

Rutherford realized the bouncing alpha particle revealed an atom that was totally unexpected. It had no familiar analogy on earth. So Rutherford looked for one in the heavens. He pictured the atom as a tiny solar system. Electrons, tiny particles of negative electricity, orbit around a minute positively charged object called the nucleus. Rutherford calculated that the nucleus was ten thousand times smaller than the atom itself. That's why only one in 8000 alpha particles bounce back - they're the ones that hit the tiny nucleus by chance - the rest whiz by without hitting anything.

The first astonishing consequence of this idea is that the Rutherford's atom is almost entirely empty space. That's why nearly all the alpha particles race through gold atoms as if there's nothing there. There really is nothing there. Consider the bizarre implications of Rutherford's atom by imagining it on a bigger scale. If the nucleus were the size of a football, the nearest electron would be in an orbit half a mile away. The rest of the atom would be completely empty space.

Let me explain it another way. So if you sucked all the empty space out of every atom in my body, I would shrink down to a size smaller than a grain of salt. Of course I'd still weigh the same. And if you did the same thing to the entire human race then all six billion of us would fit inside a single apple.

The atom was unlike anything we had ever encountered and it would only get stranger and stranger. Almost immediately a problem surfaced and it was a big one. According to the tried and trusted science of the time, the electrons should lose their energy, run out of speed and spiral into the nucleus in less than a blink of an eye. Rutherford's atom contradicted the known laws of science. The atom didn't care that it defied scientific convention. It's almost entirely empty space and it was going to stay that way. I show no signs of shrinking to the size of a grain of salt, and the Earth is, well, the size of the Earth. It's not getting smaller. Not surprisingly all the established scientists of the day, including Einstein were baffled. Scientific ideas they'd put their faith in all their lives had failed completely to explain the atom.

Chapter 3: The Quantum Nature of the Atom

The atom now required a new generation of scientists to follow in Rutherford's footsteps. Bold, brilliant and above all young - it was crucial they had no loyalty or attachment to ideas held by previous generations.

One of the first of this new breed was Neils Bohr. He sailed from Denmark in 1911 and made his way to English soil. Having finished his studies in Copenhagen, Bohr decided to move abroad and be at the center of the new physics. The trail led him to Britain, Manchester University and Ernest Rutherford. Bohr made it his mission to solve the puzzles of why the atom didn't collapse, and why there was so much empty space. As one of the new breed of theoretical physicists, he was fearless in his thinking and was prepared to abandon common sense and human intuition to find an explanation.

So in a leap of genius, he started to look for clues about the atom's structure not by looking at matter but by examining the mysterious and wonderful nature of light. Atoms and light clearly are connected. Most substances glow when they're heated. And for centuries, people had realized that different substances glow with their own distinctive colors, a bit like a signature - so the green of copper, the yellow of sodium, and the red of the lithium. These colors associated with different substances are called spectra. Bohr's great insight was to realize that spectra are telling us something about the inner structure of the atom, that they could explain all that empty space.

Bohr's idea was to take Rutherford's solar system model of the atom replace it with something that's almost impossible to imagine or visualize. So sensible ideas like empty space and articles moving around in orbits fade away and they're replaced with something that's one of the most misused and misunderstood concepts in the whole of science - the quantum jump.

It takes most working physicists years to come to terms with quantum jumps. Bohr himself said that if you think you've understood it then you haven't really thought about it enough. So I'm going to take a deep breath and in under thirty seconds try and explain to you one of the most complicated concepts in the whole of science, but one that underpins the entire universe. Bohr described the atom not as a solar system but as a multi-story building. The ground floor is where the nucleus lives. With the electrons occupying the floors above. Mysterious laws mean the electrons could live only on the floors, never in between. Other mysterious laws mean sometimes they can instantaneously jump from one floor to another. These are what we call quantum jumps. Bohr had absolutely no idea what these laws were, but thinking like this allowed him to make a startling prediction.

When electrons jump down from a higher floor to a lower one, it gives off light. And more significantly the color of that light depends on how big or small a quantum jump the electron makes. So an electron jumping from the 3rd floor to the 2nd floor might give off red light and an electron jumping from the 10th floor to the 2nd floor a blue light.

To test his new theory Bohr used it to make a prediction. Could it explain the mysterious signature in the spectrum of hydrogen? After months of calculating furiously, he finally came up with a result. And his prediction…was surprisingly accurate. For the first time ever, it looked like the spectrum could be explained. And back in 1913 that was big news.

But Bohr's new idea rested on a single, seriously controversial supposition. Why should the electrons in an atom behave as though they were in a multi storey building? Why should they magically perform 'quantum jumps' from one story to another? There was no precedent for it anywhere else in science. When one physicist claimed the jumps were nonsense Bohr replied, "Yes you are completely right, but that doesn't prove the jumps don't happen only that you cannot visualize them."

But not being able to visualize things seemed to go against the whole purpose of science. Older scientists in particular felt that science was supposed to be about understanding the world. Not about making up arbitrary rules that seem to fit the data. Conflict between the two generations of scientists was inevitable. Bohr's weird new atom and his crazy quantum jumps were a shot across the bow of traditional, classical science and the old school reacted angrily.

Leading the traditionalists was a giant of the physics world, Albert Einstein. He hated Bohr's ideas. And he was going to fight them - anything to save the world of order and common sense from this assault by madness. Bohr, though, was undeterred, and as the 1920s dawned, the battle lines for one of the greatest conflicts in all science were drawn.

So far the debates about the new atomic physics had been polite and gentlemanly. Now the two sides wheeled out their biggest guns, two of the greatest names in physics. They were two very contrasting characters who loathed each other. For the new revolutionary science was a buttoned-up, uber-competitive German called Werner Heisenberg. For the conservatives was a debonair, Byronesque Austrian called Erwin Schrodinger.

Chapter 4: The Atom's Wave-like Nature

Erwin Schrödinger - passionate and poetic, a philosopher and a romantic - he wrote books on the ancient Greeks on philosophy on religion. He was influenced by Hinduism. He was also a very flamboyant character, cool, suave, sophisticated, a dapper dresser and a big hit with the ladies. Schrodinger's promiscuity was legendary. He had a string of girlfriends throughout his married life, some of them much younger than him. In 1925, thirty-eight year old Schrödinger stayed at the alpine resort of Arosa in Switzerland for a secret liaison with an old girl friend whose identity remains a mystery to this day. But their passion proved to be a catalyst for Schrödinger's creative genius. Another physicist said of Schrodinger's week of sexually inspired physics, "He had two tasks that week, satisfy a woman and solve the riddle of the atom. Fortunately he was up to both."

He took De Broglie's idea of mysterious pilot waves guiding electrons around an atom one crucial step further. He argued that the electron actually was a wave of energy, vibrating so fast it looked a cloud around the atom. A cloud-like wave of pure energy. And what's more, he came up with a powerful new equation, which completely described this wave, and so described the whole atom in terms of traditional physics. The equation he come up with we now call Schrodinger's Wave Equation. It's incredibly powerful. What's unique about it is that it features a new quantity called the wave function which Schrödinger claimed completely described the behavior of the subatomic world. Schrodinger's equation and the picture of the atom it painted, created during a sexually charged holiday in the Swiss Alps once again allowed scientists to visualize the atom in simple terms.

It's hard to overestimate the relief Schrodinger's ideas brought to the traditional physics community. Strange though his picture of the atom was, at least it was a picture. And scientists love pictures - they allowed them to use their intuition. But there still was a deep nagging problem, one that the radicals felt Schrodinger just couldn't reconcile. His new theory still couldn't account for Bohr's strange instantaneous quantum jumps.

The time had come for the radicals to hit back. In the summer of the same year, one of Niels Bohr's protégés, Werner Heisenberg, was traveling to an obscure island off the north coast of Germany. He was fiercely competitive and took Schrodinger's ideas as a personal affront. He felt strongly that the strangeness of the instant quantum jumps was actually the key to understanding the atom. He thought the atom was so unique and unusual it shouldn't be compromised through a simple analogy like a wave, or an orbit or even a multi story building. He believed it was time to give up any picture of the atom at all.

Chapter 5: The Dual Nature of the Atom

Werner Heisenberg - one of the true geniuses of the 20th century - young athletic, a great mountain climber, an excellent pianist, he was also an exceptional student. At the age of 20 he was well on his way to finishing his PhD and being courted by the great universities across Europe. Now in the summer of 1925 he was suffering from a particularly bad bout of hay fever. His face was swollen up almost beyond recognition. He decided to escape alone to this beautiful but isolated island of Helgoland. He walked the beaches, he swam he climbed the rocks. And he pondered.

Ever since he'd encountered atomic physics, Heisenberg felt in his bones that all human attempts to visualize the atom, to model it with familiar images, would always fail. The atom, he believed was too capricious, too strange, to ever be explained that simply. So, he decided to abandon all pictures of it and describe it using pure mathematics alone. But as he pondered he realized that the atom didn't just defy visualization; it even defied traditional mathematics.

It was while he was here on Helgoland that Heisenberg had an incredible revelation. He realized that in order to describe certain properties of atoms he had to use a strange new type of mathematics. It seems that certain properties - like where an electron is at a given time and how fast it is moving - when multiplied together, the order which you multiply them matters. Let me try to explain. If we multiply two numbers together it doesn't matter what order we do it in, so three times four is the same as four times three.
But when it came to atoms Heisenberg realized that the order which you multiply quantities together gave a different answer. This quickly led him to other discoveries and he was convinced that he'd cracked the code of the atom. That he'd somehow found the hidden mathematics within.

He was so excited. He was also very scared. That night he climbed to the top of a rock and sat there till dawn. He called it his night of Helgoland. When he returned to his university in Gottinham he told his colleague Max Born about it and they then worked together intensely for several months developing a whole new theory of the atom - a theory that we today call Matrix Mechanics.

Matrix Mechanics uses complex arrays of numbers rather like a spreadsheet. By manipulating these arrays, Heisenberg and his mentor the brilliant physicist Max Born could accurately predict atomic behavior. But for Einstein and the traditionalists this was pure scientific heresy. An atom can't actually be a matrix of numbers. Surely we're made of atoms not numbers.

Back in Copenhagen, Bohr and Pauli were thrilled with Matrix Mechanics. So what if we couldn't imagine the atom as a physical object. They exulted in the purity of the mathematics and launched into vicious attacks against Schrödinger's vulgar sensual waves. Heisenberg wrote, "The more I reflect on the physical portion of Schrödinger's equation the more disgusting I find it...In fact it's just bullshit." But Schrodinger was equally scathing of Heisenberg saying he was "repelled by his methods" and found his mathematics "monstrous."

In Munich in 1926 their enmity began to reach boiling point. Schrödinger was to give a lecture on his wave equation. Heisenberg scraped together the money to travel down to Munich for the lecture to finally come face to face with his rival. What was at stake was more than just Heisenberg's reputation. He believed Schrodinger's simplistic approach wasn't just misguided, but totally wrong. And his intention was nothing less than destroy Schrodinger's theory.

Schrödinger delivers his lecture on the new wave mechanics to a packed audience. There is standing room only. He writes down his new wave equation. To Schrödinger this describes a real physical picture of the atom with electrons as waves surrounding the atomic nucleus. 24 year old Werner Heisenberg is in the audience. He can hardly contain himself. At the end of the lecture he stands up and delivers a monologue attacking Schrodinger's approach. For Heisenberg it's impossible to ever have a picture of what the atom's really like.

The audience is on Schrodinger's side. They much prefer his simple physical interpretation to Heisenberg's abstract complicated mathematics. Heisenberg is booed, he's told to sit down and be quiet. He leaves the lectures sad and depressed. Heisenberg returned to Copenhagen, with his confidence severely dented. There at the Institute, he and Bohr reached their darkest moment. Almost all of the scientific community was against them. They felt isolated, desperate, their backs were against the wall. Despite this they stubbornly refused to give up their controversial theory.

This attic room was Heisenberg's study back in 1926. Bohr would come up here night after night, where he and Heisenberg would argue about the meaning of the new quantum mechanics. They would argue so passionately that on one occasion apparently Heisenberg was reduced to tears. And then as Heisenberg stared out of his attic window in despair at the park below, an extraordinary thought occurred to him. It struck him why an atom can't be visualized, why it can't be understood intuitively. It's not just because it's tiny, tricky and difficult, it's because it's inherently unknowable.

He realized that there was a fundamental limit to how much we could know about the sub atomic world. For instance if we know where an electron is at a particular moment in time then we cannot know how fast it is moving. But if we knew its speed we wouldn't know its position. This ambiguity isn't a shortcoming of the theory itself nor is it due to the clumsiness of the way we carry out our measurements, but a fundamental truth about the way nature behaves at the sub atomic scale.

It became known as Heisenberg's Uncertainty Principle and it's probably the most profound, incredible yet unsettling concepts in all of science. What Heisenberg had uncovered through his abstract matrix mechanics was a deep and shocking truth about the atomic world. Atoms are willfully obscure. We can never fully know an atom's position and speed simultaneously. The atomic world just refuses to allow that to happen. It was completely mind-boggling. But once they accepted it, Heisenberg and Bohr found the boost of confidence to be even more bold.

Chapter 6: The Uncertainty Principle

They realized 'Uncertainty' forced them to put paradox right at the very heart of the atom. Atoms aren't just unimaginable, they're self-contradictory. They behave both like particles and waves. And it gets weirder. When you're looking at an atom, it behaves like a spread out wave. But when you look to see where it is, it behaves like a particle.

This was insane. First atoms couldn't be visualized at all, now it seems they change completely in character depending on whether or not you're looking at them. The Uncertainty Principle had changed everything. It revealed a shocking contradiction at the heart of nature. Everything we see is made of atoms, and yet atoms themselves are unknowable. They can only be understood through mathematics.

For the first time, for Bohr and Heisenberg everything about the atom fell into place. By the autumn of 1927, full of confidence and smarting for a fight, they knew they were finally ready to take on the conservatives.

For this physics showdown, they chose the Solvay Conference in Brussels. All the world's leading atomic physicists would attend. If Bohr and Heisenberg were successful, then they would lead a total scientific revolution. This is amazing. I'm looking at original footage of the Solvay delegates coming out of these doors. There's Bohr talking to Schrödinger and there's Heisenberg behind them. And there's Pauli, a strange looking guy. And there's Einstein coming down with a big smile on his face.

For the week of the conference all that delegates could think and talk about was Bohr's Quantum Mechanics. With Uncertainty now a central plank, it was a truly formidable theory. And over the week the final showdown played out between Bohr and his arch-rival, Albert Einstein. Einstein hated Quantum Mechanics and every morning he'd come to Bohr with an argument he felt picked a hole in the new theory. Bohr would go away very disturbed and think very hard about it and by the end of the day he'd come back with a counter argument that dismissed Einstein's criticism. And this happened day after day until by the end of the conference Bohr had brushed aside all of Einstein's criticisms and Bohr was regarded as having been victorious.

And with that, his vision of the atom, which became known as the Copenhagen Interpretation, was suddenly at the very heart of atomic physics. At the end of the conference they all gather for the team photo. Never before or since have so many great names of physics been together in one place. At the front the elder statesman of physics

Hendrick Lorentz, flanked on either side by Mme Curie and Albert Einstein. Einstein's looking rather glum because he's lost the argument. Louis de Broglie has also failed to convince the delegates of his views. Victory goes to Neils Bohr. He's feeling very pleased with himself. Next to him one of the unsung heroes of quantum mechanics the German Max Born who developed so much of the mathematics. And behind him the two young disciples of Bohr, Heisenberg and Pauli. Pauli is looking rather smugly across at Schrödinger, like the cat who's got the milk.

This was the moment in physics when it all changed. The old guard was replaced by the new. Chance, a probability became interwoven into the fabric of nature itself and we could no longer describe atoms in terms of simple pictures but only using pure abstract mathematics. The Copenhagen view had been victorious.

Although Einstein went to his grave never believing Quantum Mechanics, Solvay 1927 was the turning point at which the rest of the science establishment came to embrace the Copenhagen Interpretation. And that interpretation is still accepted today. All the physics that I use in my research, certainly the quantum mechanics that I teach my students, and which fills the text books on my shelves, is based on ideas that were hammered out and crystallized here at the Solvay Conference in October 1927. In a sense everything I know about the way the world around me is made up started here.

The Quantum Mechanical description of the atom is one of the crowning glories of human creativity. Over the last eighty years, it has been proven right time after time, and its authority has never been in doubt. It’s a monumental scientific achievement. Between 1905 and 1927 science changed our view of the world, it also changed our view of science itself. As scientists probed the tiniest building blocks of matter, they created the most successful and powerful theory ever, quantum mechanics. It allows us to describe what everything in the universe is made of, how it interacts and how it all fits together. But it comes at a huge price.

At its most fundamental level we have to accept that nature is ruled by chance and probability. Heisenberg's Uncertainty Principle dictates that there are certain limits to the kinds of questions we can ask of the atomic world. And most crucially while we now know so much more about what an atom is and how it behaves, we have to give up any possibility of imagining what it looks like. Our human nature has forced us to ask questions of everything we see about us in the world. What we have discovered has been beyond our wildest imagination

This Educator’s Guide is produced by Centre Communications, Inc.
For Ambrose Video Publishing, Inc.

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Educator’s Guide and Script by
Ron Meyer and Mark Reeder

Published and Distributed by...
Ambrose Video Publishing
145 West 45th St., Suite 1115
New York, NY 10036
1–800–526–4663
24–Hour Fax 212–768–9282
http://www.ambrosevideo.com

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