**What makes up nothing?** What makes up the empty space outside of the Earth, above the atmosphere, and fills most of the universe? For centuries, this problem has been puzzling physicists, confronting them to develop more and more satisfying theories to describe reality. After all, how do we define the intangible space we live in after we take out all the air, the furniture, the people, and anything we usually call mass? How do we define what we usually call a vacuum? Is it simply made of nothing, or is there something inside? On the surface, this question is extremely paradoxical and self-contradicting. Isn’t nothing, just made of nothing?

Or is it? The straightforward answer to this question is: we don’t know yet, at least not exactly. **There have been many efforts made to develop a satisfying theory of reality**: how the universe starts, how black holes explode, how light moves, or how supernovas expand. Yet after all, strangely, when we ask ourselves the simple question: well, what is nothing? We still cannot answer. I’m no physicist, but today I’ll share with you what I found not from the complexities of the math equations, but from retracing the footsteps of our physical understanding of the vacuum. By looking at how people came up with new explanations, how they confronted themselves with nature’s paradoxes, we can all perhaps gain some insight using this story of “nothing” on how not knowing something itself contains great value.

Our journey begins quite recently as compared to the vast thousands of human development, to the discovery of a strange wave phenomenon.

The world is filled with all sorts of waves: sound waves, water waves, guitar string waves. These waves must also travel through a medium: sound waves most commonly through air in our daily experience, and water waves through water. **But in the early 19th century, there came an astonishing discovery.** Light, something once thought of as a particle, was shown to behave like waves. At the time, it was the prevalent idea that everything wavelike should travel in a medium. **There really is no straightforward alternative to it.** After all, just like how water waves must travel on water, it’s our intuitive understanding of the world that guides us into thinking there must be a medium. But light travels through the vacuum, and shouldn’t there be nothing in a vacuum and hence there should be no medium at all? This paradoxical question that started this talk was presented to physicists at the time.

People had to figure a way out of it, which was when physicist Maxwell began propagating a famous concept called the luminiferous ether. Essentially, he stuck with the medium idea and thought everything must move through an intangible substance called the ether, which they thought filled the vacuum. Eventually, the theory was put to the test with the famous Michelson-Morley experiment. **Sadly, no evidence matched Maxwell's predictions.** Seeing this failed experiment, Maxwell and a few other physicists decided to stick with the ether theory and changed it to acknowledge the experimental failures. However, experiments didn’t align with their predictions again. Specifically, an object travelling with some speed will be contracted by a certain amount, meaning that it will be shorter when it’s moving than when it’s standing still. This was directly opposite of what Maxwell and his companions predicted, and they changed the theory once more to fit with the new data. Eventually, this cycle continued for some time before the entire theory became extremely complicated, complicated to an extent that it was very likely false.

That was when Einstein’s theory of special relativity jumped in. Einstein’s theory included no ether at all and explained everything that Maxwell had a hard time with using merely a correction in spacetime. In other words, space and time itself is changed a little bit in moving objects. This ridiculous, yet simple idea fits all experiments. It was perfect, but only to the extent that it seemed a little too perfect. **At the end of the day, shouldn’t there be a medium so light can pass through?** **What happened to that idea?** As a result, Einstein’s theory wasn’t successful at first and people thought it was merely an artificial mathematical tool, something temporary before the actual medium theory gets worked out. **After all, how are we supposed to believe that some certain waves can just travel through a sea of nothingness and magically pass energy?** Our intuition permits nothing else but a medium.

I’ll come back to this idea later.

Eventually the ether theory was abandoned, not because it was wrong, but because it was too complicated and predicted random things we can’t test.

Things changed when we moved into the early 20th century, where people discovered that things on the smallest scale, on a scale smaller than all our senses can feel, don't behave in a way we commonly think they would. This was the discovery of quantum mechanics. Two of the astonishing basic principles of quantum mechanics were this: first, energy comes in discrete chunks, we cannot have whatever amount of energy we want; second, we cannot measure both the position and momentum to 100% certainty. This means that I basically cannot stand still in principle, and my actual position can vary greatly.

The discrete energy and the uncertainty principle are two of many very counterintuitive yet interesting ideas in this subject. And the real fun starts when you actually apply these principles, accompanied with experiments, we find that light are actually particles in quantum mechanics. **But didn’t we say light was a wave? Hence we are faced with another paradox, and we try once again to figure out what this wave-particle duality thing called light is.** We can see a nice pattern recurring as well: we find a seemingly solvable paradox, and we try to solve it using new ideas and push forward our understanding of the world. In this example, physicists combined field theories with quantum mechanics and developed what is known as quantum field theory.

Behind me is a computer simulation of what we now think constitutes the vacuum. What you are seeing here is something called quark-and-gluon waves coming in and out of existence in this tiny tiny box. It shows for utmost precision that the vacuum is not as empty as we thought it was. **Once in a while, you might see quarks that’s one of the fundamental particles of the universe pop in existence under accumulation of these waves, living perhaps for just a slight fraction of a second.** This relates back to the uncertainty principle, the fact that nothing can sit still, so these waves fluctuate and bubble around.

Quantum field theory tells us to utmost certainty that everything is made of waves. Just to quickly demonstrate how accurate it actually is, here is the theoretical prediction and experimental value of g, a value that relates to an electron's magnetic properties. The two values match up perfectly to the 12th digit, meaning a difference only one in a billion, showing just how accurate our understanding of the world is.

**But let us just step back for a moment, and think of what all of this actually says.** From the ground up, everything is waves, coming in and out of existence. The things we may call electrons or particles are merely just ripples of these waves through space. But does that really give us everything? The question that seems to guide us here is the “how” question. How our universe behaves, how big the value of g is, how waves ripple, etc. We’re leaving out one essential question that constitutes greatly our intuitive understanding of the world: the “why” question. For example, why do we live in a three-dimensional space? Why do time only move forward? **Such questions seem extremely unanswerable.** It is what it is, as some may say. We don’t ask commonly “why we live in a 3-D space” because we are born into it. It’s just like how we don’t wake up and ask ourselves “why we are living still” because we are indeed living. **Although there are answers to them, and some of these questions may be valuable, we don’t ask them because they don’t disobey our intuition for the world.** But once in a while, we face something like quantum mechanics, which completely destroys everything we are familiar with. **Here, asking the “why” question makes more sense, because we don’t understand it.** Quantum mechanics says nothing is deterministic anymore, our existence is governed by a wavefunction, a probability distribution. It also says that the wave function collapses once someone observes, say an electron. But why is it that way? Or, if we take a step back if that question seems too distant, how can I accept this ridiculous idea that basically says I do not exist here if no one observes me?

The answer we have currently, as I’ve stated at the beginning, is we don’t know. **Now you see the real question we’re asking when we ask “what is nothing.” It’s not how these wavefunctions work, it’s making sense of how they work.** We don’t know because even after all this accuracy, all these correct predictions, we cannot explain what our theory actually *is*. All we can do is calculate. And that itself is the answer for a major group of theorists: we don’t need to understand what our theory *means,* we just need to be able to predict things, shut up and calculate. However, even after all this accuracy in data, we cannot explain a ton of things such as dark matter or dark energy. So after all, we do need to understand what quantum field theory and quantum mechanics *means*. At this current stage, sadly, we don’t.

**At the start of this talk we encountered the idea that light can travel through vacuum.** Einstein said there was no ether and light simply *can* cross a sea of nothingness. He wasn’t wrong, the fluctuations we saw aren’t the medium we were looking for, it was simply a showcase of how unstable things are, so waves bobble around. **But it’s still a drastically different picture a hundred years ago. As we continually ask “whys,” we can now make much more sense of why light can travel through nothing. Although the ether theory ended up way too complicated and distant from experiments, it pushed forward our understanding of space and vacuum.** Perhaps the same thing can be said about our current dilemma as well. It is only when we don’t understand something, when there’s a sharp contradiction in our theory against our intuition, can there be progress.

And that is all I want to share today. I remember reading this interesting story physicist Richard Feynman once told to explain to his students the nature of a series of lectures he gave to his students on light. Imagine thousands of years ago, a few Mayan citizens wanted to learn how to subtract numbers. They find their priest, and the priest says “well, suppose we want to subtract 236 from 584. First count out 584 beans and put them in a pot. Then take 236 beans out of it. The remaining ones will be your answer.” Now, there is no way we can solve for instance 1 million minus 1 million using this method. But the point is, after all the fancy tricks, taking beans out of a pot is really what subtraction is. **And that is very similar to how people wish we can treat a controversial and extremely complicated subject like quantum field theory.** After all the calculations, all the complicated constructions, we should turn back to ourselves and ask “well, what does it all mean?” And we hope that will bring progress in the future.