QUÂNTICO

Episode 02 - I HAVE A THEORY

"Italic": Excerpt pseudoscience speech

[in brackets]: sound effect

OPENING: PHYSICS IN the 19th century ***

[intro - bass]

> **Pablo Saldanha:** So there were some phenomena at the turn of the nineteenth century to the twentieth century that were not explained by what we call classical physics.

Leo - You may already recognize this voice from our first episode, it is from Pablo Saldanha, Professor at the Federal University of Minas Gerais and quantum optics researcher. Here Pablo is describing to us the panorama of physics around the year 1900.

> **Pablo Saldanha:** So classical physics was developed since Galileo, Newton who developed the laws of mechanics and then came thermodynamics, electromagnetism, optics. So you had a set of areas of human knowledge that you had what we called classical physics to explain. It explained most of them very well. It explains the generation of electromagnetic waves, it explains the formation of the rainbow, it explains the movement of the planets around the sun…

Leo - With this we see that most of the physical phenomena in our daily lives and most of the physics we learn at school fit within classical physics.

> **Pablo Saldanha:** So it provided a very large technological development for humanity and a very effective knowledge of nature.

Gláucia - In fact, classical physics was so successful that a good number of physicists at the end of the 19th century were satisfied and proud of physics as a whole. Some of the most confident people even said that there were no longer any great things to be done in physics, everything was already more or less closed. There is a famous phrase from that time attributed to Albert Michelson, an American physicist who won the Nobel Prize in 1907, in which he says that [radio filter] "the great fundamental principles have already been firmly established… the next truths of physics must be sought after the sixth decimal place".

Lu - I suppose this sixth decimal place thing has something to do with calculations, is that it?

Gláucia - That's it, basically he said that we just had to improve the precision of the calculations and get the numbers right after the decimal point. For example, we just don't know if a certain quantity has the value 12.000001 or 12.000002, but other than that, we already understood everything, at least that's what he thought.

Leo - Yes, it's true that he won the Nobel Prize, but he made a big mistake on this one, because classical physics is cool and everything, but as Pablo had already warned...

> **Pablo Saldanha:** But there were some things that were not explained.

[identity - bass and congas]

Gláucia - Some of these unexplained things that Pablo is talking about are precisely the tip of the iceberg of quantum theory as we understand it today. But okay, what is this quantum theory thing after all? In this episode we will talk about how quantum theory arises, where we find it in our daily lives and in which direction it is heading.

I'm Gláucia Murta, I'm a physicist and researcher in quantum cryptography.

Lu - I am Luciane Treulieb, journalist and science popularizer.

Leo - I am Leonardo Guerini, mathematician and researcher of the foundations of quantum theory. This is the podcast O Q Quantico. In the first block, we will talk about three phenomena that were fundamental to the emergence of quantum theory. In the second block, we talk about how knowledge of this new theory ended up generating a series of cutting-edge technologies that we have today, and in block 3 we summarize how our current understanding of quantum is producing the technologies of tomorrow. Come with us as we start Episode 2: I have a theory.

[Opening song and cat]

BLOCK 1: QUANTIZATION *** ********

Leo - As we already mentioned in the opening, around the year 1900, there were some problems that the physics of that time, which today we call classical physics, could not handle. We start by talking about three of these phenomena that didn't have an explanation, but which had incredible consequences and are interconnected with each other. These phenomena are: [plim] the iron bar that glows with different colors as its temperature increases, [plim] the electrons rotating around the nucleus of the atom that strangely did not fall into the nucleus and [plim] the light that ripped out electrons from some materials but not from others. We will present these phenomena here in a summarized way with the help of Pablo.

Gláucia - The first of them is super common, and you've certainly come across it.

> **Pablo Saldanha:** When you heat an object, for example, if you think of an iron bar, if you heat it a lot, it will turn red, orange, even yellow.

Lu - Wait, heating an iron bar until it turns yellow isn't super common, right... unless you're, I don't know, a blacksmith who makes your own barbecue skewer...

Gláucia - Hmm, okay, but for example when you see a hot coal on the barbecue, the phenomenon is the same. Basically, the point is that when materials get hotter, they emit radiation, and this radiation changes color as the temperature increases. The coal heats up so much that it starts to emit a reddish glow. And here I'm talking about hot coals, okay? And not the flame. Sometimes the flame has even gone out, but the coal is still emitting this reddish radiation.

Lu - Okay, you said that coal emits radiation. But a very basic and earlier question: what is radiation?

Gláucia - Well, here in this context, we can say that radiation is basically a synonym of electromagnetic waves. We're going to talk more about this, but there are electromagnetic waves in many things that we know well: for example, the microwave that we use to heat food, there are also radio waves, cell phone waves, X-rays… these are all electromagnetic waves.

Lu - So, just to confirm that I understand correctly, is radiation the same thing as an electromagnetic wave?

Leo - That's it, same thing. So in the example of burning coal, the reddish light that the coal is emitting is an electromagnetic wave.

Lu - So light is also radiation?

Leo - Yes! Visible light, which is the light that the human eye can see, is also a form of radiation. We only see light in a range of frequencies, which goes from red to violet, but some nocturnal animals, such as mosquitoes and some types of snakes and bats, for example, can see radiation in other frequencies too, such as infrared. So these animals can see in the dark. And this is also how night cameras work.

Lu - It’s just that we’re used to thinking of radiation as something dangerous, right, atomic radiation, from nuclear power plants…

Gláucia - Well, this is a specific type of radiation, it is super energetic radiation. To explain it better, we need to bring some technical terms, but let me know if it gets too complicated. There are three features involved here: the energy of this radiation, its frequency, and the color we see. The higher the frequency, the greater the radiation energy. We only see from red, which is a less energetic light, to violet, which is a more energetic light. So these even more energetic waves, like nuclear radiation, we don't see because they have a frequency above violet.

Leo - But these are all examples of radiation. As Gláucia said, what changes from the infrared radiation that is captured by mosquitoes, to the light from the lamp in your house, to the X-ray, from when you take an x-ray, is how energetic the radiation is.

Gláucia - Yes, and going back to the iron rod and coal, they were already emitting radiation even before they got very hot, but we didn't see it. But when you increase the temperature, the radiation energy also increases. Then, at a given moment, the temperature is so high that the radiation enters the visible spectrum, and we start to see it in the form of a reddish glow.

Lu - Wow, it's a lot of new information, but I think I got the main point: when we talk about radiation, the higher the frequency, the greater the energy... that's it, right?

Leo - That, and vice versa too. But at the end of the 19th century, it was not possible to explain exactly the behavior of this radiation that was emitted. More specifically, the mathematical formulas proposed to describe this phenomenon, which were based on classical physics, made predictions that were completely inconsistent with what was observed in reality. And that was a problem.

> **Pablo Saldanha:** So why it emits the colors that it emits even in a hot bar, classical physics did not explain.

Leo - The second phenomenon that we want to bring here, we don't see in everyday life, but everyone has heard about it. At the beginning of the 20th century, another basic thing that was not explained…

> **Pablo Saldanha:** … is that experiments began to show that matter was made of atoms. So at a certain point it was discovered that atoms had a negative electrical charge around a central positive electrical charge, which is what we call the atomic nucleus.

Lu - Okay, I think I remember that, this is that figure we know from high school, the atom formed by a nucleus and with electrons orbiting around it.

> **Pablo Saldanha:** And then a fundamental question is, how to explain this? What is an atom fundamentally? One way to understand [...] is to make an analogy with the planetary system. That the solar system is similar to this. We have a sun, [...] And we have the planets revolving around it. [...] And you explain this very well. But what's the problem with using this same model to explain an atom? The problem is that the atom is made of charged particles, with an electrical charge.

Gláucia - This comes from electromagnetic theory, which is one of the high points of classical physics. This theory says that everything that has an electrical charge, such as an electron, emits radiation when it moves, the same radiation that we were discussing just now.

Lu - I didn't quite understand. Could you talk about this using something from our everyday lives, like the microwave from before?

Gláucia - For example, a cell phone antenna works based on this idea. The antenna needs to communicate with your smartphone and vice versa, right? It does this by encoding information into electromagnetic waves. But then there have to be very specific waves for them to understand each other, right? So how does the antenna generate these waves? In a very simplified way, it uses oscillating electrons, that is, moving electrons. Depending on how the electrons oscillate, they generate different waves that will propagate through space and reach your cell phone. So, by controlling this oscillation, the antenna is able to generate waves precisely to send the desired information. That's the point: In general, moving electrons generate electromagnetic waves, which is another name for radiation.

Lu - Hmmm, okay, it is a little better.

Gláucia - I know it's difficult, but don't give up. And going back to what Pablo was saying, this becomes a problem if we want to explain the atom as if it were a mini solar system, with the electrons revolving around the nucleus. Because if the electron moves, it emits radiation, and all radiation has a certain amount of energy. Therefore, emitting radiation would mean losing energy.

> **Pablo Saldanha:** So these electrons spinning, they would emit radiation, lose energy and end up falling into the nucleus in a time much less than a second. So people couldn't explain how it is possible to have atoms and then how it is possible to have matter in general. So it's a very fundamental question. This, with classical laws, could not be explained.

Leo - To top it off, there was a third problematic phenomenon that emerged at that time, which became known as the photoelectric effect.

Gláucia - The photoelectric effect is cool because it shows the relationship between two fundamental elements of physics: the electron and light. Experiments began to show that when we shine light on plates of a certain material, say cesium, that material starts to emit electrons. In other words, it's as if we turned on a flashlight in front of this plate and the light from the flashlight knocked out some of the electrons that were there, orbiting the nuclei of the atoms. However, if we turn on this same flashlight in front of a plate made of another material, say a lithium plate, this second plate does not emit any electrons.

Lu - Okay, but what's the problem? If they are two different materials, it doesn't seem so strange if they behave differently.

Gláucia - Well, so far so good. But if we understand that this is a general principle, that light makes materials emit electrons, the natural thing would be to think that what is missing in this case is to increase the intensity of the light. So let's change our flashlight, which wasn't very big, for a bigger flashlight. Still nothing happens... The lithium plate still doesn't emit any electrons. And we can increase our light source even further, we can get a giant reflector, from a football stadium, which still won't remove electrons from this second plate. And at the time people didn't have a good explanation for this.

Leo - So, to resume: we have [plim] the iron bar that glows with different colors as its temperature increases, [plim] the electrons rotating around the nucleus of the atom that strangely did not fall into the nucleus and [plim] the light that stripped electrons from some materials but not others. And the cool thing is that each of these problems was solved with the same seemingly extravagant idea: quantization. [blunt] As the word itself says, quantization is the fundamental idea on which quantum theory was created, the name quantum comes from there.

Lu - But what exactly does quantization mean? Because when I searched for quantum on the internet, I came across those topics that we showed in the last episode. So, for example, there are people who would associate quantum with pseudoscientific talk about the power of the mind:

[radio static]

> *“This is quantum physics in action. This is a manifestation of reality. This is the observer in full effect.”*

[radio static]

Leo - [filter off] …which is totally absurd…

Lu - There are people who would say that quantum is the key to understanding ufology:

[radio static]

> *“Quantum physics and ufology, how can we apply these more advanced discussions of quantum physics in relation to the UFO phenomenon.”*

[radio static]

Leo - [filter off]…which is complete nonsense…

Lu - There are people who would conclude that quantum is the theoretical basis of homeopathy:

[radio static]

> *"When I discovered that homeopathy could be explained through quantum physics, that was a spectacular thing for me."*

[radio static]

Leo - [filter off]…which has nothing to do with it…

Lu - And there are people who would even think that quantum teaches how to travel in time:

[radio static]

> *"It is only in conscious experience that we seem to be moving forward in time. In quantum theory, you can also go back in time."*

[radio static]

Leo - [filter off]…I wanted to go back in time just to not have heard that…

Lu - As you may have guessed, none of these audios help much to define what quantization actually is. Luckily, we have Gláucia and Leo to help us with this.

Gláucia - The word Quantization is basically related to the property of that which is not continuous, and which is made up of packages, of units. For example, apples, in the supermarket, apples are quantized... I buy 1 unit, or 2 or 3... I don't buy half an apple. And going more towards physics... matter is quantized because it is made up of atoms, that is, if you zoom in on the wooden table in your kitchen, you will see that it is not continuous, but made up of these little individual blocks, which are atoms.

Leo - The word quantum itself, right, comes from Latin, associated with these fundamental quantities that form things. So the atom would be the quantum of matter.

Gláucia - And an example of something that is not quantized is the speed of your car, because you can accelerate and increase speed continuously. If it were quantized, your car would always be jerking, because when you accelerate it would go straight from 10km/h to 20km/h, for example, then another jump to 30km/h. In other words, something being quantized means that it only appears in packages, which are multiple integers of a fundamental unit.

Leo - Today, these examples of the apple, the atom and the speed of the car help us understand what quantization is. But how did scientists at the beginning of the 20th century arrive at this idea? To explain this, we can go back to our three problems. In the first, that of the iron bar, the first obstacle was to find a mathematical formula that correctly described the relationship between the temperature of the bar and the color of the emitted radiation. Then, in the year 1900, a German physicist called Max Planck decided to use a mathematical trick that solved the problem: he made an assumption, somewhat pulled out of the hat, that this radiation was always emitted in little packages, in an integer multiple of copies of the same fundamental unit.

Gláucia - In other words, he assumed that the energy emitted by the bar was quantized.

Leo - With this, he came up with a formula to explain the observations of this type of experiment.

Lu - You had already talked about formulas and mathematical models before. Why is it so important to have a formula for this kind of thing?

Leo - Okay, that's a very good question, but we'll be able to give a better answer to it in the third block, when we discuss these things a little more. So keep the question and we'll come back to it when we get there, okay?

Lu - Okay.

Gláucia - So, going back to Planck, he managed to create a mathematical model to explain the iron bar problem using the idea that the energy emitted was quantized. But if the energy of light is quantized, this means that the light itself is made up of little packets… But Planck didn't actually believe it, that there really were individual packets of light. For him, quantization was nothing more than a mathematical trick that well described the problem in question. Planck, like everyone else at the time, firmly believed that light was continuous.

Lu - Wait, I'm in one of those moments where I don't even know what to ask. The part that I understood well is the speed of the car, which when we look at the speedometer it continually increases. So isn't light like speed? Isn't it continuous?

Gláucia - Well, no! And that's surprising, right? Quantization introduces the idea that light is not continuous, and that it is therefore made up of little packages. We'll talk more about this in a moment. For now we will just say that Planck was looking for a mathematical model, not necessarily related to the reality of the things, and he achieved this model. Even though he had to resort to quantization.

Leo - This changes a lot when, a few years later, the solution to the second problem is found, that of the electron around the nucleus. Remembering, electrons orbit the nucleus of atoms, but apparently they should lose energy and end up falling into the nucleus. But that doesn't happen, because, once again, quantization comes to save the day.

Gláucia - This time the person who ventured to think outside the box was Niels Bohr, a Danish physicist who in 1913 realized that to explain the behavior of an electron well, that electron could not be free to rotate around the nucleus in an arbitrary way. It had to be restricted to occupying only a few specific orbits, which represented the different energies it could have. In other words, what Bohr proposed and saw that it made perfect sense was the quantization of the electron's orbit.

Lu - Okay, those are those electrons making circles around the nucleus that we see in school, right?

Gláucia - Right. In fact, this drawing of circles around the nucleus is not that correct. Today we have a better understanding of the atom, but for now we will continue with the Bohr model. So, what Bohr said is that the electron was not attracted until it fell into the nucleus of the atom because it could only move in specific orbits. And this empty space between the orbits acted as if it were a barrier to make the electron behave properly, following its route. And each orbit corresponds to a specific energy of the electron. This implies that the electron’s energy is also quantized.

Lu - But what does it mean that the electron's energy is also quantized?

Gláucia - It means that just as only some orbits are allowed for the electron, the energy that the electron has can also only take on some specific values, depending on the orbit it is in. In other words, it is as if the electron's energy was also organized in little packages and the electron only loses or gains energy when it jumps from one orbit to another.

Leo - And that brings us to our third problem, of light stripping electrons from metal plates, and how solving it ties all of these things together. As we said, the light from the flashlight stripped electrons from the cesium plate, but not from the lithium plate. The one who had the greatest insight to explain this was he, the most popular physicist of all, Albert Einstein. This happened in 1905, a little before Bohr discovered the orbits of the electron. Einstein explained this situation by telling anyone who could listen: light is quantized. This isn't a mathematical trick, like Planck thought, it's the physical nature of light.

Gláucia - In other words, light has a fundamental unit, as if it were a block of light, and every ray of light is formed by a certain number of these blocks. This little block is what we today call a photon. So, for all intents and purposes, this was the birth of the photon.

Lu - Okay, but how does this explain the behavior of light on the plates?

Gláucia - So what was understood is that electrons can absorb photons and they can also emit photons. And what makes electrons move from one orbit to another is exactly the absorption of a photon, which gives it the exact energy to move between levels. The electron absorbs this photon with specific energy and is able to move to an outer orbital layer, further away from the nucleus. In this case, we say that the electron is excited.

Leo - And the opposite can also happen, the electron can emit a photon, reduce its energy and therefore move to an orbit closer to the nucleus.

Gláucia - Yes, in this case we say that he decayed. So the photoelectric effect is when a photon, individually, gives enough energy for an electron, which is there in the outermost layer of the atom, to completely escape the nucleus.

Leo - When you turn on the flashlight in front of the metal plate, you are bombarding that material with photons. Depending on the material of the plate and the energy of the photons, the electrons in the outermost shell absorb these photons, gain enough energy to declare independence from the nucleus and leave from there.

Lu - I don't know why, but this description reminds me a little of that movie 'Chicken Run'. Would this be like 'the electrons' run'?

Leo - Like that. But this run of electrons from each material is different, because each material has its own personality. Cesium, for example, has more adventurous electrons in its last layer, which need less energy to leave. The electrons in the last layer of lithium, on the other hand, will require more energy to do so. So the crux of the issue here is not the intensity of the light you are throwing, but rather how energetic that light is.

Gláucia - In other words, if a yellow flashlight has already failed to remove electrons from a plate, there is no point in connecting a yellow light reflector on top of it as no electrons will be removed. So it makes much more sense to exchange the yellow flashlight for another flashlight that emits violet light, for example. Because what you need is radiation that has a higher energy.

Lu - Okay, let's see if I understand: from the flashlight to the reflector I'm increasing the intensity, the amount of light I'm throwing. But that alone is not enough to strip electrons from the lithium plate, what I really need is to increase the energy of the light, which has to do with the color. That's it, right?

Leo - Right. [congas] Well, it's worth mentioning that we're not explaining all the details of how quantization solves all of this (for that we would need an entire semester in college), but the idea is that with these three phenomena it becomes clear how quantization opened the doors for us to better understand how fundamental objects, such as atoms, electrons and photons, behave.

[transition - cat]

BLOCK 2: CURRENT QUANTUM TECHNOLOGIES **********************************

Leo - Well, perhaps you've already heard that the Nobel Prize is the biggest award in physics. So it's cool to think that the explanations for these three phenomena that we have discussed so far were exactly what guaranteed Max Planck's Nobel Prize, received in 1918, Albert Einstein's Nobel Prize, received in 1921, and Niels Bohr's Nobel Prize, received in 1922. But that's not the only reason we wanted to talk about these phenomena to you.

Gláucia - It was also not just to illustrate how powerful the idea of quantization is, that solved the different fundamental problems that were emerging at that time. We wanted to bring these three phenomena here because understanding them brought a giant conceptual advance. Understanding the structure of the atom, the behavior of the electron and how it interacts with light was so important that today, more than a hundred years later, we are still riding a wave of technologies based on this.

> **Ingrid Barcelos:** We know the atom very well, so this is one of the good things about exploring these things that are well described by quantum mechanics.

Lu - This is Ingrid Barcelos, she is a physicist and researcher, and works with nanoscale materials at Sirius. In case you didn't know, Sirius is the largest particle accelerator we have here in Brazil, it's in Campinas, in São Paulo.

Ingrid Barcelos: And then there is the battery, the phone, we can use materials that work better, charge faster, but all of this, we can only explore these materials, which is what I do here in the laboratory where I work, given this understanding that we have today.

Lu - For Ingrid, understanding these first quantum phenomena that we have been discussing in the episode triggered a technological revolution.

Ingrid Barcelos: For people who work in experimental physics, I always say that this was a revolution, and why? Because it allowed us to understand, then visualize and then manipulate the materials.

Leo - And it's not just Ingrid who calls this a revolution. Many people refer to this boom in quantum-generated technologies as the "first quantum revolution." This is no coincidence, a significant part of the United States' GDP comes from technologies of quantum origin, there are people who say that this contribution represents a third of the GDP. This happens because the entire electronics segment depends heavily on quantum science.

Ingrid Barcelos: Everything we use today is based on microchips, transistors, computers, notebooks, everything.

Gláucia - The transistor is a small piece that is essential for microprocessors. It is present in computers, cell phones and many other electronic devices. It is considered one of the greatest technological advances of the twentieth century.

Ingrid Barcelos: So these transistors are elements that we use to pass electrical current to amplify some signal [...] so it is an electronic component that you can turn on and off, and what we associate with turning on and off: 0 and 1.

Gláucia - Have you ever heard that your computer works in binary language, that is, based on zeros and ones? Well, the transistor is the hardware, that is, the physical component behind these zeros and ones. Transistors are largely responsible for enabling information processing within chips.

Leo - In a computer, we first translate the task to be done into binary code and then use transistors to represent this binary language through the passage or not of electrical current. Here, the contribution of quantum is more precisely due to the miniaturization of transistors.

> **Ingrid Barcelos:** If we think that the first computer occupied an entire floor of a building and today we have a computer that fits in my hand, this is only possible because we can use materials with a very reduced thickness.

Gláucia - More specifically, a key point was to develop semiconductor materials, that is, materials that, depending on the situation, can conduct electrical current and function as a 1, and, depending on the situation, can act as insulators, interrupting the electrical current and functioning as a 0.

Leo - Now, do you know which materials are definitely bad for this? The metals.

> **Ingrid Barcelos:** For example, metal, metal is a terrible material to make a transistor, because any thermal excitation already has conduction, so you can't turn it off.

Leo - In other words, copper, which is the metal generally used in electrical wiring, would always work as a 1, because it always lets current pass. On the other hand, an example of a semiconductor material that is useful for building transistors is silicon. This is where the name “Silicon Valley” comes from to designate the place in California where many electronic chip factories emerged.

Gláucia - Today, a high-end cell phone has more than 15 billion transistors, each of which can switch between 0 and 1 a billion times per second. Now, if you can fit billions of little pieces like that in the palm of your hand, imagine how big they are, right? Building little pieces like this, so small, was only possible because of quantum science, which explains well the energies of the electrons in an atom. And this helps us, for example, to combine silicon with other materials so that one part of the transistor conducts electrical current well and another part conducts it poorly, functioning as an insulator.

Leo - Another person we talked to about this is Gabriela Barreto Lemos, who is a physics professor at the Federal University of Rio de Janeiro and a quantum optics researcher, who is also very active in promoting diversity and equity within physics. Gabriela agrees with the fundamental role of quantum in our computers.

> **Gabriela Barreto Lemos:** In fact, we are waiting for the great quantum computer, but, in a way, every computer we have uses quantum theory.

Leo - But in addition to the transistor, there are also other super important technologies that we can mention.

Gláucia - In fact, the photoelectric effect that Einstein explained is the basic premise of the solar panels that we have today: sunlight falls on a plate, which emits electrons, which generate an electric current. Of course, this is a very simplified way of describing the process. Since 1905, there has been a huge advance in both experimental physics and engineering to make these plates viable and efficient.

Lu - Speaking with Gabriela, she told us that this is not the only application of the photoelectric effect.

> **Gabriela Barreto Lemos:** And who would have thought, everyone has a photoelectric effect at home, right? Which is the basis of digital cameras. [...] Your cell phone's camera itself is based on the photoelectric effect, which is an effect that was discovered at the end of the 19th century and that was only understood with Einstein, in a beautiful work, in which he basically invented the photon, right?

Lu - But where else can we find technologies that were influenced by quantum?

Gabriela Barreto Lemos: For example, MRI scan, right? This is an application of a quantum effect. [...] The laser itself, people, which is used in everything.

Lu - Is the laser used for everything?

Gabriela Barreto Lemos: So the laser, the laser we use, to shave hahaha, we use the laser to do surgery, eye surgery, then we use it to cut [...] we use the laser in fashion, you've seen it, right, these materials are laser cut. We use lasers in a lecture to point. We actually use it all the time. And the laser is a quantum phenomenon, right.

Leo - Here it is worth telling some details. The difference between a laser and the light from any lamp is that the light from the lamp is all messed up. For example, in this common cold light bulb, which you probably have at home, there is radiation of all colors that ends up generating that white color that we see. Polarization, which is another property of electromagnetic waves, in this case is also disorganized, it varies in all possible directions. [chaotic drums] Making an analogy with sound waves, it's as if we were playing several drums at the same time that are of different sizes and in a chaotic way, out of rhythm.

Gláucia - [chaotic drums fade] So what does a laser pointer do? You know,... that laser pointer that we use to point in a slideshow or to play with cats. Then, the laser pointer uses energy from its battery to excite electrons in a specific material. As a result, these electrons become excited and go into a more energetic orbit. But this excited electron tends to decay, returning to its previous orbit. And when that happens it emits a photon. In Ingrid's words…

Ingrid Barcelos: We have an electron from an atom that is stimulated to a higher energy level, so we call it stimulated emission, and this decay will emit monochromatic light.

Gláucia - Monochromatic light… that is, light of just one color, or just one frequency, as we said before. So the laser light is a well-behaved light that can be precisely controlled. We say it is a coherent light. This stimulated emission is a process that organizes the emission of light, because this emitted photon is always emitted with the same characteristics: the same energy, and therefore the same frequency, and the same polarization. [chaotic drums transitioning to drums in sync] It's as if we filtered out the sound of different drums beating out of time and only drums of the same size were left, playing in sync. That's the laser.

Leo - And there's no need to repeat which theory made all these technologies possible…

[drums]

> **Ingrid Barcelos:** And we can only derive information from this, because the atom is very well described by quantum mechanics.

[transition - cat]

BLOCK 3: THINGS ARE EVEN WEIRDER ***********************************

Leo - So until now we've talked about how those three quantum phenomena that we brought up at the beginning of the episode contributed to the development of many of our current technologies. But when we ask an expert on the subject if these are the phenomena that best represent quantum theory, Pablo Saldanha, who was already talking to us before, responds that…

> **Pablo Saldanha:** I would say no, because they were the first, right, and they motivated the construction of the theory. But today they are very well understood within the theory and they are not the ones that most clearly express the strangeness of this quantum world.

Leo - In fact, they only scratch the surface. Quantum is even stranger and more beautiful than that. To talk about this, we need to tell you a little more about how quantum theory emerged. Compared with the theory of relativity, for example, although relativity appeared at more or less the same time and also reached impressive conclusions, it can be seen as a generalization of Newton's theory of gravitation. In other words, relativity generalizes classical results, which means that we have a well-known starting point to kick-start the discussion.

Lu - And in the case of quantum, what would the starting point be?

Leo - Well, there is none. The scientific community was faced with a series of phenomena that they didn't even know where to begin to understand. When we started studying very small objects, such as the electron or the photon, more and more phenomena began to appear that seemed incredible, different from anything we encounter in our daily lives. Gabriela Lemos describes this feeling in a really cool way:

> **Gabriela Barreto Lemos:** It's a bit like Alice in Wonderland. [...] For me, I felt like Alice who had, you know, gone down that hole and had found, like, completely crazy phenomena, you know, and fascinating, and fascinating. But they don't make sense outside the hole, right?

Gláucia - So because of these crazy phenomena, as Gabriela said, researchers were forced to create a mathematical model practically from scratch. Here is a good moment to return to the question that Lu asked at the beginning of the episode, why it is important to have a formula or a mathematical model associated with a physical phenomenon.

A mathematical model is important because it represents a deeper level of understanding. It is an abstraction that can go beyond a specific situation. So, for example, when we have a formula or a mathematical model that relates the temperature of an iron bar and the radiation it emits, we can extrapolate and predict what happens in many other situations beyond the iron bar. We can even deduce what radiation is emitted by much larger objects and at much higher temperatures (such as the stars). So with a good mathematical model, instead of exploring a phenomenon in practice, we have the option of exploring this phenomenon mathematically.

Leo - On the other hand, having a mathematical model also allows you to relate things through mathematics that apparently had no relationship. A classic example of this is pi, that number that starts with 3.141592 and so on. Although pi historically appears associated with the proportion of the elements of a circle, we also find it in formulas for many things that at first glance have nothing to do with a circle, such as the movement of a spring and the number of collisions of billiard balls in a given situation, just to give a few examples. These non-obvious connections act as bridges between distant topics, increasing our overall understanding.

Gláucia - Rafael Chaves, Professor at the Federal University of Rio Grande do Norte and researcher in the area of quantum information, talks a little about how this process of formulating quantum theory happened.

> **Rafael Chaves:** So throughout, let's say, from 1905 until about nineteen twenty-something, twenty-five was basically a collection of experimental data and different models, mathematical attempts to explain these phenomena.

Gláucia - Look how interesting, despite having the experimental results as a guide, it also took a good dose of trial and error until the researchers discovered the mathematical language that represents quantum systems well. As Rafael says, quantum theory…

> **Rafael Chaves:** … it is a mathematical framework, a set of mathematical rules that summarize, that in a certain way encodes in themselves the essence of quantum physics. So quantum theory is made up of postulates, of mathematical rules that we don't prove. We accept it.

Gláucia - This mathematical framework works, it is effective. With this in hand, we can predict what will happen in experiments, even if the results are counterintuitive. Perhaps an example of this is the light, which intuitively we would say is continuous, but quantum theory concludes that it is quantized.

Leo - So the theory's predictions worked, but there was a bitter taste of dissatisfaction, because it was something like “doing it like this works, but I don't really know why it's like this”.

Gláucia - In other words, although mathematics represents physics well, there was no well-understood physical principle associated with this mathematics.

Lu - What do you mean by that?

Leo - To make an analogy, imagine that you are trying to understand how the tides work. Right, in certain periods the tide rises, in other periods the tide goes out. At a certain point, you notice that this is related to the moon, that high tide occurs whenever the moon is in certain positions in the sky and in certain phases. Once you understand this, just look at the moon to predict what will happen with the tide. Today we know that this relationship is due to the force of gravity that the moon exerts on the ocean.

Gláucia - In other words, whether the tide will be high or low basically depends on how far the moon is from that point in the ocean.

Leo - Now, if we didn't know anything about gravity, the relationship between the moon and the tide would seem more mysterious. And this is the case with quantum. We might think that quantum phenomena were like the tide, and that quantum theory worked like the moon. In other words, by studying the theory, we predicted what would happen in the experiments, but in this case we did not have a more fundamental physical principle, such as the force of gravity in the case of the tide and the moon, explaining the connection between theory and practice.

Gláucia - Even so, as we mentioned earlier, once you have this mathematical model, quantum theory, you can start doing the opposite. Now that you have used the first experiments to formulate a theory, you can mathematically explore the theory to formulate new experiments.

Lu - Over what period of time did this happen? Back in the last century? Or now?

Gláucia - Well, we can say that this started at the beginning of the last century. After quantization appeared to explain those three isolated phenomena that we discussed at the beginning of the episode, a more general theory, encompassing all of them, began to be formulated in the 1920s. And once we have the quantum theory formulated, we reach a new level. If quantization had previously made important practical contributions, such as describing the behavior of the atom, now quantum theory goes a step further and describes a number of oddities that had never been witnessed until that moment.

Leo - Just to give you an idea of how weird things are, we're going to list some of these weird things here with a very short description of each one. Maybe you've already heard of some.

Gláucia - We have: superposition [tum], which says that a quantum system can be in a combination of two distinct states.

Leo - Entanglement [tum], which Einstein described as a “spooky action at a distance”, and this ended up generating a lot of confusion and a lot of quality research, including the 2022 Nobel Prize.

Gláucia - Uncertainty relations [tum], which say that we cannot determine all the characteristics of a system at the same time.

Leo - Intrinsic randomness [tum], which means that we cannot know for sure the result of an experiment before carrying it out.

Gláucia - And we could continue, mentioning contextuality, non-locality, no-cloning, teleportation... It was thanks to the mathematical formulation of quantum theory that all these strange and complex properties could be revealed.

Lu - Okay, but I, at least, have never heard of most of these things... in the next episodes we'll talk more about them, right?

Gláucia - About some, yes. Mainly those that appear most in pseudosciences, such as superposition and randomness.

Leo - But with a lot of these phenomena, when someone initially predicted that these things were possible… people found it hard to believe. They said it was a mathematical whim that would not be reflected in the physical world.

Lu - Why did they say that?

Leo - First, because there was this suspicion that the physical principles behind quantum theory were not clear. And second, because these were counterintuitive things, very different from the physics we knew and also different from everything we see in our daily lives. As Gabriela Lemos points out:

> **Gabriela Barreto Lemos:** We live in a world where we don't notice quantum phenomena on a daily basis. So, we develop a way of thinking that is somewhat incompatible with quantum phenomena. [...] And someone tells you that the world works in a way that you don't understand, it's very bad, it's very strange.

Lu - Yeah that's very strange…

Leo - Well, although counterintuitive, the experiments confirmed, time after time, the predictions of the theory. It followed that idea of "I don't really understand why it works, but it works". And here the discussion from our first episode, about falsifiability, reappears. It is precisely because it generates so much distrust that people tried to show that quantum theory had some error, that there must be something wrong with this story. Over the decades, many, many experiments have been carried out. And guess what? Quantum theory has survived all these tests. Today it is considered one of the most successful and well-established physical theories from an experimental point of view.

Gláucia - But given so many strange things, it took decades and decades of studies and experiments for the community to be convinced that these properties that we mentioned before, randomness, superposition, etc., despite being strange, are actually legitimate attributes of quantum systems. And it is precisely by exploiting these properties that we are about to take the next big technological step. As Pablo Saldanha says...

Pablo Saldanha: But then there are several weird questions about quantum mechanics that were previously a curiosity, right? And not now, now they have practical applications.

Leo - So, the precise manipulation and refinement of phenomena such as superposition and entanglement is exactly what is leading us to the so-called “second quantum revolution”, which has already begun and will be responsible for the definitive establishment of quantum computing, quantum cryptography and of the quantum internet, among other things. To give you an idea, in 2022, a record for global investments in quantum technology startups was reached, reaching the mark of 2.35 billion dollars. Furthermore, it is estimated that the market size of these technologies could exceed 100 billion dollars by 2040. Today, the sum of public investments announced for the coming years in the world, with the aim of boosting research and education in quantum technologies, reaches to almost 35 billion dollars, with China leading with more than 40% of these investments.

Lu - And Brazil doesn't want to stay out of this, right? To give some examples of what has been happening across the country: the Ministry of Science, Technology and Innovation, in partnership with the Brazilian Industrial Research and Innovation Company, Embrapii, announced in 2023 an investment of 60 million reais for the creation of the Center of Competence in Quantum Technologies, which will be led by Senai Cimatec, in Salvador. The Rede Rio Quântica project recently received resources from different funding sources to enable the implementation of a quantum communication network in the Rio de Janeiro city. Furthermore, since 2020, a group of scientists has been creating a roadmap for the implementation of Quantum Technologies in the state of São Paulo. And Brazil recently launched the first federal and state funding initiatives aimed exclusively at research in the areas of quantum technologies.

[drums]

Gabriela Barreto Lemos: …much faster computers, making encryption, therefore, much safer, making the internet much safer, right? [...] So, for you to do, understand, solve very complicated systems, right? In chemistry, physics, biology, there are very complicated systems, our computers can't do the math, and neither can we. But with the development of quantum computers we can move forward.

[transition - cat]

CLOSING ***

Leo - We are coming to the end of this episode, where we wanted to bring a panoramic view of quantum theory and how it has transformed and will transform the world. We want to end by tying these with other things that we hear about quantum, but that are not really scientific.

Gláucia - We talked about how some of the great names in physics, such as Einstein, Bohr and Planck, laid the foundations for understanding the structure of the atom, electrons and their interactions with photons. These interactions belong to the domain of quantum theory, but this is such a fundamental notion that in one way or another it is present in most current technologies. But then why don't we call the laser a quantum laser, or current computers quantum?

Leo - Compare it with the term 'atomic'. It refers to atoms, which make up all matter. But just because every bomb is made up of atoms doesn't mean they are all atomic bombs.

Gláucia - It's similar with quantum. If we push it, many things, at some level, depend on the properties of the atoms, their electronic structure or some form of radiation. But that doesn't mean these things should be called quantum. And here we could mention a lot of products that advertise themselves in this way, like the quantum mattress that appeared in the last episode.

Leo - Furthermore, a good part of the technologies that are yet to come are based on these strangest and most curious concepts that we mentioned in this last part of the episode, such as superposition and entanglement. In other words, quantum theory is a great option for those who like unusual ideas.

Gláucia - This makes it a great place to look for analogies. In fact, there are many serious thinkers who seek inspiration from quantum theory to apply to other areas of knowledge. But there are also people who try to push it and make analogies for other purposes…

Leo - Think about the idea of quantization, the electron is there in an orbit, cute, and suddenly, it absorbs a photon and jumps to another orbit. This is exactly the origin of the expression “quantum leap”. But “quantum leap”, today, has become synonym for “radical change” and is certainly among the most used expressions in quantum pseudoscience. For example, in the book Quantum Healing, we find a passage that says: [radio filter][typewriter] “the cooperation of mind with matter causes an unexpected quantum leap; but, like other mind-body episodes, it takes place in a mysterious way.”

Gláucia - It’s okay to use “quantum leap” as an analogy. We already said that, in our opinion, science does not have a patent on the word “quantum”. But when you make the analogy this way, it seems like quantum would explain this “mysterious way” that the book talks about. As Rafael Chaves says, this example of the transition of an electron to another energy level is really a good example of a sudden change…

> **Rafael Chaves:** But what is important to say is that the analogy ends there. It's simply an analogy, simply another way of thinking about the same topic. But it does not mean in any way that the rules, the consequences of quantum theory can be used to explain these phenomena.

[identity track - bass]

Leo - Over the next few episodes, we want to bring you the quantum concepts that appear most in pseudoscientific content. Have you ever heard of things like the vibration of success, or the frequency of health? Well, we often hear that these ideas are based on quantum phenomena. But what do waves, particles and wave-particle duality, which are concepts that appear even in quantum science, have to do with this? We tell you in our Episode 3: Particularly wavy.

[transition - cat]

CREDITS ** *************

[identity track - drums, then bass and piano]

Leo - Most of the topics we discussed here in this episode, especially the historical part of the formation of quantum theory, appear in more detail in the book ‘Incerteza Quântica’, by Rafael Chaves, which is an excellent book and which we highly recommend if you want to know more about these things. Rafael Chaves was our interviewee here today, and you also heard excerpts from interviews with Pablo Saldanha, Ingrid Barcelos, and Gabriela Barreto Lemos. Many thanks to our interviewees.

The transcript of the episode and the translation into English are available on our website www.ufsm.br/oqquantico, as well as links to various information about quantum technologies that we mentioned here in the episode.

If you liked the episode, you can help by recommending it to friends who are interested in the topic. Also follow O Q Quantico on Instagram @oqquantico and be sure to rate the podcast on your favorite podcast platform.

In this episode we use excerpts from the movie What the Bleep Do We Know!?, from 2004, from the YouTube channels Laércio Fonseca and Kelly Lemos: chronic pain, and from the book Quantum Healing, by author Deepak Chopra.

Lu - Q Quantico is presented by me, Luciane Treulieb, Gláucia Murta and Leonardo Guerini.

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Thanks for listening and see you in the next episode!

POST-CREDIT STORY **

> **Ingrid Barcelos:** I have a friend, who had the courage to call me, knowing that I am a physicist, to tell me that she had gone, “you are not going to fight with me, but I went to a therapist, she recommended something to me, she said it was new product and then she charged I don’t know how many reais for a quantum package”, I stopped, it’s because I don’t know what I told her like, “but what did she give you?” “She gave me some lights, she showed me the thing that was blinking” you see, quantum, light... then she started talking and I said, I'll be very honest with you, “I have a degree in physics, a master's degree, a doctorate in physics , I took an infinite number of quantum subjects, yes many [...] I can't think of anything you told me that she did with you that applies to anything I've ever seen in my life, and it's based on what knowledge you think your therapist has to give you a quantum cure because I think like this: If I were to do anything that had to do with quantum, I would want to do it with someone who worked with quantum, you won't go to the butcher shop to ask for math lessons, you go to the butcher shop to buy meat from a butcher, you go to the pharmacy to buy medicine, you don't go to buy medicine, I don't know, at the bakery, so I think it's very strange that you would want anything quantum, with someone who doesn't have training.

[cat]