Hello and welcome to Quantum Stories, a three-part mini-series explaining aspects of quantum mechanics at a simple level as part of Explorathon 2021. Episode 3: Here and there. In this episode, we'll explore further the wave nature of particles and quantum mechanics.

We will take the concepts introduced in the previous episode a step further and tackle concepts like superposition and entanglement. The scene was well set for this episode by the previous episode, so we will just move straight on. Part one, the wavefunction.

Last episode we talked about the nature of waves and particles and how the line between the two is blurred. I introduced the idea that the microscopic particles we are interested in within quantum mechanics, for example, the electron, can be described as waves.

The basis of much of quantum mechanics relies on the fact that the state of the system at any time can be described by a function: the wavefunction. Much like a wave of water is described by ripples on the surface of the water,

the wave function describes the ripples of the quantum state through space. Knowledge of this wavefunction of a quantum system, for example, the wavefunction of an electron allows us to calculate the results of any measurement on that system. If we know the wavefunction,

then we can calculate the dynamics of the system through the Schrodinger equation, the wave equation introduced in the last episode. There is much more to the wavefunction, and we'll explore some of that in this episode. Part two, superposition.

The fact that waves could be added together to get stronger peaks and interfere is the result of something called the superposition principle. Superposition here means the combination of properties. If the two waves interfering are described by two functions,

then it would be natural to think of this interference as the sum of these functions. This is somewhat like what happens in quantum mechanics, but it's a bit different. It is best to understand it like this. If we have a system, say a particle like the electron.

Then, as we have already discussed, it's state, that is its physical properties, can be described by a wavefunction. But we know that something like a particle can have different states. For example, it could be stationary or moving.

And these different states are described by different wave functions. Now here comes the odd part of quantum mechanics. If we do not measure the particle, then we have no way of knowing if it is moving or stationary. So if we want to describe the particle before we measure it, we need to describe it as in the combination

of both possible states. This combination is then given by the sum of the two wavefunctions. These wave functions describe the stationary electron or particle, at the moving one. If we know the probability of either being stationary or moving, for example, is half and half like a coin flip,

then we know the numbers that we should multiply each wavefunction by in the sum. In the half and half coin flip, we would write the quantum superposition state as 1/2 times the first wavefunction, plus 1/2 times the second wavefunction.

So that's all great, but this all leads us to the famous paradox of quantum superposition illustrated by Schrodinger's cat. This is a rather terrible thought experiment for any cat lovers out there. But it's the wording that we are somewhat stuck with and that's been popularised.

We have a box with a rather intricate set up. It has a bottle of poison which is released or opened dependent upon a radioactive source. If the radioactive source has decayed, releasing radiation, then the bottle is opened and the poison is released.

We rather cruelly put a cat in this box. The cat will eat the poison and sadly die of the radioactive source decays. We close this box. Then the question becomes, is the cat alive or dead? Unless we open the box, which is in fact, taking a measurement,

we cannot know. Much like when the electron or particle was moving or stationary, unless we measured it, we didn't know if it was moving or stationary. So the thinking is that until we open the box, the cat is in a "superposition" of being alive and dead.

The question of whether the cat is alive or dead without opening the box is really a question for the topic of quantum foundations. I'm not going to cover quantum foundations during this mini-series. The reasons are that I am no expert,

and it is a field somewhat divided from the rest of quantum physics in many ways, where questions wander more into the realms of philosophy than science sometimes. Now, I'm not saying that wandering into philosophy is a bad thing, but it means that questions quickly become deep and numerous and hard to answer.

The answer to the question "is the cat dead or alive" has many potential answers, and it is a debated subject to this day. Thankfully, this is a thought experiment, and there is no cat stuck in the box in the name of physics waiting for us to decide the answer to this question.

Part three entanglement. The possibility of a quantum state to exist in a superposition opens up an intriguing and very different possibility. See, we have two particles that can both be either stationary or moving. We could imagine having two boxes with two cats in it being alive or dead, but I much prefer the more humane picture of discussing

two particles moving or being stationary. Say we know that only one of the particles can be moving. The other one needs to be stationary. But then we would write the full quantum state of the two particles as a sum made up of two components.

The first component of the sum is made up of the first particle moving and the second particle being stationary. The second component of the sum is made up of the first particle being stationary, and the second particle moving.

The two particles are said to be entangled. Their individual quantum states are reliant on the other particle's quantum state. This raises an interesting property. If we measure one of the particles, we instantly know the quantum state of the other without even measuring it.

But this sounds odd. How can we know the state of something we have not measured? Also, we know that information is bounded by the fundamental speed limit of the speed of light, nothing including information, can move faster. But we know what the state of the non-measured particle

is instantly. There is no delay for the information to travel. We immediately, as soon as we measured the other particle, know what the state is. This led to what Einstein called spooky action at a distance. This story of entanglement has been confirmed in many experiments.

There are several interpretations to reconcile entanglement with the spooky action at a distance. However, again, this wanders into the realm of quantum foundations in many ways. And the simple truth is that I'm not qualified to really weigh in on this issue, and nor do I think that it has even been solved yet.

Part four, if only all, was so simple. In three parts, I really covered all I wanted to say in this episode. It kind of doesn't meet up well with my nice four part structure I've been doing in each episode. So I could not quite resist adding on a slight discussion relating to my own research at the end of this

episode. From what I've said so far it sounds trivial to know the wavefunction and quantum state of a system. And I've said that after we know the wavefunction, we can predict a lot about the quantum system. In fact, everything pretty much.

Well, sadly, or in my case, happily for my salary. Knowing the wavefunction of a quantum system is not so simple. Most quantum systems are collections of many particles interacting with each other. They're not quite as simple as the single electrons and particles and balls

we've been talking about in this mini series. We could perhaps make a good guess of the wavefunction of an individual particle, but knowing the wavefunction of a collection of many particles is an entirely different problem. Solving for the wavefunction of these many particle systems is difficult and requires the development of new approaches and thinking of how

to obtain them. Part of my research day to day really comes down to this problem alone. We know a quantum system. And we want to know the properties of it. But to know its properties, we need to know the wavefunction.

So we need to find ways of figuring out its wavefunction. Before we leave the story for now, I wanted to reiterate how odd the two facts are that we've been discussing. That is, that superposition and entanglement are in contrast to our everyday lives.

Everyday objects around us do not exist in a state of either moving or being stationary. They are just one of them. They move or they do not. But this, along with the wave particle duality we were talking about last episode, is really, I think in many ways the second most weird thing about quantum mechanics, and that is

that for this mini-series, this is the last episode of the mini-series. If you've listened this far or just to this episode, I would like to deeply thank you. I had grander ambitions for this mini-series at the start.

We were going to go into more topics and explore the current quantum technologies boom that is the other part of my research focus. But time is precious. And I left the production of these episodes far too late to meet the Explorathon deadline. [Editors note: They were worth the wait!]

Maybe I will speak again sometime. If they're useful at all, even to a small number of people, then I will retain my grander plan and produce some more of these episodes. If not, then no issue. Writing and producing these episodes was a great experience for me.

And if nothing else, gave my wife a good laugh when she heard what I was up to when she was out with our daughter. I would like to once again thank the Explorathon team of the University of Strathclyde.

And again, thank you for listening. And I hope you will join me in any potential future endeavours.