LECTURE 3: THE EQUATIONS START ASKING THE SAME QUESTION

The Vallico Academy Lecture Series

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0. OPENING CALLBACK

1

By now you know this is coming.

Two modes of attention. You've had it twice: once at the end of the Burton lecture, once at the opening of the Plotinus lecture, and I promised I'd keep coming back to it until I finally told you what it's called. I haven't told you yet.

So. You know the shape of it. One mode is narrow, instrumental, good at manipulating the world and bad at asking what the world actually is. The other is broad, holistic, comfortable with paradox, and the only one capable of taking seriously the possibility that the observer and the thing being observed might not be cleanly separable.

Last time I showed you that the entire esoteric tradition (Plotinus, Boehme, Blavatsky, all the way to Faggin) is built entirely in the second register. And I showed you what happened to it: the Scientific Revolution ruled that the first mode's questions were the only serious ones. Casaubon in 1614, proving the Hermetica weren't ancient. Descartes in 1637. Newton in 1687. The tradition didn't die. It went underground. The questions weren't answered; they were declared out of order.

Tonight I want to show you something that should, by rights, be embarrassing to anyone who thinks that story ended there.

In the twentieth century, a small number of the most rigorous scientists on the planet (working from equations, not visions, not pewter dishes catching the sunlight, not Ouija boards in upstate New York) started arriving at conclusions the esotericists would have recognised immediately. Not because they were reading Plotinus. Because the mathematics kept pointing somewhere the mathematics wasn't supposed to point.

And the response of the establishment was, almost word for word, identical to 1614. The questions were ruled out of order. The people asking them were told to stop. One was called a Trotskyite and exiled to Brazil.

Watch for this as we go. The first mode, in physics, built a theory (quantum mechanics, viewed through the lens of the so-called Copenhagen interpretation) that works perfectly for making predictions and refuses, on principle, to say what is actually happening underneath those predictions. The second mode (the minority, the ones who kept being told they were wrong) insisted that you don't have a theory of reality until you have an actual picture of it, not just a very accurate calculator.

That argument happened, in concentrated form, in one room in Brussels in 1927. We'll get there. First: what is quantum mechanics actually for?

Now I'll tell you that in a second, but first I should tell you that this is largely a repeat - a massively oversimplified repeat - of a talk I first gave in 2009 to about 250 people at the Cambridge University Physics Society. The audience were mainly professional physicists and students - so there were quite a lot of equations in the slides - but in principle it was for a general audience, so there were jokes and stuff too. Out of sheer laziness, I was going to reuse the same slides and just skip the overly math ones. But! On reflection I've made some new ones that fit in with the slide style of this series which I decided I quite liked.

2

OK, let's have an introductory slide, a bit like the Greeks in Two Minutes from last time, but this time for physics.

Two things I - as a former theoretical physicist - want to clear up.

First, what is theoretical physics for? You might think it's to explain the fundamental nature of reality, exploring the nature of existence, objects made of matter, time and all that? A lot of people think it is. But it isn't. That's metaphysics, which is a branch of philosophy, and one which has hardly any real answers. A lot of people get very disappointed by this, beginning with Robert Hooke in the 1600s being disappointed by Isaac Newton's new theory of gravity. Newton himself said "I have not as yet been able to discover the reason for these properties of gravity from phenomena, and I do not feign hypotheses.. it is enough that gravity does really exist and acts according to the laws which we have explained". To many contemporaries this looked like ducking the issue. Hooke in particular held that as a purely mathematical definition that failed to say what gravity was in physical terms was incomplete. Nature's great forces, in his view, had to be grappled with experimentally and mechanically, not merely described mathematically.

Let me give you another example. I remember Samantha's father talking to me over dinner and trying to engage me in conversation because he knew I was a physicist, and he said "Mike, when I'm listening to the wireless I know that something is transmitted from the radio station through the air to my transistor radio. What is it, exactly." and the truth, which I probably expressed in a different way to Mr. Keil, is as follows. Let me say this slowly. Nobody - has the least earthly idea.

And the reason is that the aim of theoretical physics is not metaphysical, it is to construct a mathematical model of the universe which behaves exactly like the real one, and if you can come up with some equations to make such a model, you are said to have 'explained' whatever phenomenon you're looking at. This is what Hooke was complaining about. You can usually map mathematical objects that appear in the equations onto things that supposedly exist in real life. But you haven't really explained it, you've modelled it, and that's incredibly useful because you can make predictions, and you can use those predictions to make things and build things and design experiments and things like that. But it isn't an explanation in the normal sense, and this has led to a lot of disappointment.

And yes, I could say to Mr. Keil and I'm sure I did, well, it's the wiggles in the electromagnetic field that propagate the signal from the antenna to his, but if I say that I'm really talking about the math, the E and B fields that appear in Maxwell's equations of electromagnetism. I'm talking about the map, not the actual landscape. And certainly something is travelling through the air between the transmitter and the radio, and you can call that the electromagnetic field if you want to, but no-one knows really what it is, or how or why it does that or why it does it at the speed of light. It just does, and we have equations which if you solve them will do the same thing.

The second thing I want to discuss on my introductory slide is this. Quantum mechanics - which is what this talk is about - what is it? It's simply the branch of physics that concerns itself with very small things, like atoms and stuff like that. We are all made of atoms, and atoms in turn are made up of a nucleus containing positively charged protons and neutral neutrons surrounded by a cloud of negatively charged electrons. The protons and neutrons in the nucleus are held together by the short-range strong nuclear force, everything else is electromagnetic forces, like charges repel, unlike charges attract. Gravity on this scale is utterly utterly negligible. There's a hundred and something kinds of atom, depending on how many protons are inside the nucleus. Atoms can bind together in groups to form molecules, like the ones on the slide. Molecules can crash into each other and modify each other, and that is chemistry. Quantum chemistry if you do it theoretically and look at matter at the atomic scale.

You can see on the slide a list of the things that make quantum mechanics different to classical mechanics associated with Isaac Newton. At the atomic level, it's not just little balls pushing and pulling each other with electromagnetic forces. Something else is going on, and that results in things like wave-particle duality, quantum superposition, entanglement, and the uncertainty principle. You don't need to fully understand what is meant by these phrases, but for now the slide provides a little one-sentence summary of each one.

There's an equation you can see in the corner of the slide which you can use to calculate atomic and molecular properties - associated with the name of Erwin Schrödinger. Funnily enough that's the main thing I used to do in my physics career - we developed a method called quantum Monte Carlo which can do that more accurately than anyone else. You don't need to understand this equation, other than to know that the solution of the equation, the function you plug into it so the left-hand side equals the right-hand side, is this greek letter Psi here. It's called the wavefunction and once you know what it is it allows you to calculate things - essentially to do chemistry on a computer. Similar to the E and B fields in the electromagnetic equations, which are supposed to represent a real physical electromagnetic field that travels through space. But what does the wave function map onto in real life? Good question, and the answer to that will turn out to be (a) massively controversial, and (b) rather interesting.

1. COLD OPEN

3

Every one of these claims comes from real, bestselling books: the sort of thing you'll find on the physics shelf of any airport bookshop, and in the popular science sections of most universities.

I'm not going to tell you these books are stupid; they aren't. But I am going to tell you that what you're looking at is not a set of physical discoveries. It's a philosophical interpretation that most working physicists absorbed in their twenties and never subsequently questioned.

The claims (and you'll have seen versions of them everywhere) are that quantum mechanics proves that particles don't have definite properties until someone observes them. That observation doesn’t reveal a pre-existing reality but somehow creates it. And that this, if you follow it to its conclusion, implies that the universe is in some sense a product of consciousness.

Now. Some of you may have come across this idea in a different context: last lecture, for instance, when we were somewhere around the third century AD.

I am not going to tell you the conclusion is wrong. I’m going to tell you the path these books take to get there is wrong, and that the actual physics, properly understood, points somewhere considerably more interesting and considerably more honest. Hold what you’ve been sold loosely for the rest of this talk. Some of it is true, and some of it is the result of a philosophical choice made in 1927, by a group of very clever men who may have made it too quickly. We’re going to find out exactly what that choice was.

And if I can be a little facetious, I think physicists tend to like it this way, just because all the weirdness sounds cool and gets them more action with the opposite sex. More than the usual zero anyway. It reminds me of that Mitchell and Webb comedy sketch where Webb is at a social gathering in someone's house and when it's time for the 'what do you do' conversations he modestly let's it be known that he's a brain surgeon, and he scoffs at everyone else's lesser jobs by saying "It's not exactly brain surgery is it?". Then he meets his nemesis when Mitchell arrives at the party, and it turns out he's a rocket scientist. Quantum physicists do pretty much the same thing.

So let’s start from scratch. What does quantum mechanics actually say?

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So this is the incredibly famous maverick physicist Richard Feynman, bongo drummer, media personality, casual sexist, and brilliant Nobel Prize winner.

He will now explain the one experiment at the heart of all of this. He once spent nineteen pages of his book 'The Character of Physical Law' doing just that without, by his own admission, actually explaining it at all. He called it the experiment that contains all the mystery of quantum mechanics. He said it was impossible, absolutely impossible, to explain in any classical way. He said nobody knows what machinery produces the result. And he told his readers directly: don’t keep asking how it can be like that, because nobody knows how it can be like that.

The experiment is simple to describe. Fire electrons, one at a time, at a barrier with two slits. On the other side is a detector screen. Common sense says each electron goes through one slit or the other, and you get two bands on the screen. What you actually get is an interference pattern: the kind of pattern you’d expect if the electron were a wave passing through both slits simultaneously. Even when you fire them one at a time. Even when there’s no possibility of two electrons interfering with each other.

Change the experiment, add a detector to find out which slit the electron went through, and the interference pattern disappears. The act of finding out seems to change what happens.

That’s the mystery. And Feynman’s claim (the standard claim, the one in all the textbooks) is that nobody can explain it. That there is no deeper picture. That this is simply what reality is like at the bottom.

He was wrong. But it took twenty-five years from Solvay for anyone to say so in print, and another thirty for anyone to take it seriously.

2. WHAT QUANTUM MECHANICS ACTUALLY IS

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Before we get to what’s wrong with the standard story, we need to be clear about what quantum mechanics actually is, as a theory.

Quantum mechanics is, in its standard form, a probability calculus. You put in the initial conditions of a system, you run the mathematics, and out comes a prediction for the probability of getting a particular result if you perform a particular measurement. It is extraordinarily accurate: the best-tested theory in the history of science, accurate to twelve decimal places in some cases. Nobody disputes that.

What it does not do, in its standard form, is tell you what is happening between measurements. It doesn’t say what an electron is, or where it is, when you’re not looking at it. It treats measurement as a primitive, as something that happens, after which the system has a definite state, without explaining how or why that transition occurs.

Most physicists, for most of the twentieth century, treated the question of what’s really happening as not just unanswered but unanswerable. As the wrong kind of question. As metaphysics, in the pejorative sense.

You’ve heard that move before.

6

The standard theory has a specific problem at its core, and it’s worth stating it plainly because most popular accounts gloss over it.

The problem is this. According to quantum mechanics, a system that hasn’t been measured exists in a superposition: a simultaneous combination of all its possible states, each with an associated probability. A simple example with only two states is measuring the spin of a particle, a property of quantum objects about which the only thing you need to know is that it has to be either up or down with respect to some axis. So fire the particle through a horseshoe magnet. If it goes one way, it's spin-up, if it bends the other way, it's spin down. You've made a measurement. Before the measurement it exists as a weighted sum of up and down states - what's called a superposition. The mathematics of how this superposition evolves over time is perfectly well-defined: it obeys an equation, Schrödinger’s equation, deterministically, continuously.

But when you perform a measurement, that superposition doesn’t gradually resolve into a single outcome. It jumps, instantaneously, to one definite result. The wave function collapses. And the theory provides no account whatsoever of what constitutes a measurement, when exactly the jump occurs, or what physical process is responsible for it. Let me repeat that in a different way: it evolves in time according to Schrödinger's equation, just a function changing its shape over time, except when it doesn't, and it doesn't when someone observes it. What kind of mathematical theory is that? And what is an observer anyway, and how does it differ from merely interacting with some other object? Does the observer have to be conscious?

What the theory does instead is tell you to stop asking. Calculate the probabilities. Predict the measurement outcomes. Don’t inquire into what’s really happening between one measurement and the next. The question, in Bohr’s framework, is literally meaningless.

An aside I can’t resist, from the 2009 talk. That same year, a perfectly serious environmental-science study reported that fullerene molecules (sixty carbon atoms arranged like a football) stick to fruit flies’ feet and cripple their ability to climb walls. Real molecules, doing real mechanical damage to real feet. But fullerenes are quantum particles: fire them at a pair of slits and they diffract, exactly as electrons do, which, on the standard reading, means they have no definite properties until somebody observes them. So the problem, presumably, would go away if only the flies had the good sense not to look at their own feet.

Which brings us to a man who needed the help of someone else’s wife to write the equation we’ve been discussing, and whose most famous contribution to physics was designed to show that this situation was completely absurd.

3. SCHRÖDINGER

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At this point I want to introduce a pattern you may have started to notice. The great figures we keep meeting (the ones who pushed hardest against the boundaries of what’s officially thinkable) have a tendency to have pushed hard against other kinds of boundaries too.

Burton: twenty-nine languages, Sufi initiate, translator of erotica, probable spy, wrote the most comprehensive survey of global sexual practice ever compiled by a single Victorian. Schrödinger: theoretical physicist, Nobel laureate, and a man whose domestic arrangements would have given Burton himself pause.

In December 1925, Schrödinger left his wife in Zurich, took an unknown woman to a villa in the Swiss Alps at Arosa, and came back two weeks later with one of the most important equations in the history of science. The woman is referred to in the historical record only as the Dark Lady of Arosa. Nobody knows her name. Nobody knows what Schrödinger told her they were going to do in the mountains. What we know is that the Schrödinger equation emerged from that fortnight, and that it remains the foundation of quantum mechanics today.

He won the Nobel Prize in 1933. His wife, by accounts, was a remarkably accommodating woman. The story goes that she arranged for him, as a reward for the Nobel, to spend time uh.. tutoring two young women, Ithi and Withi, who in my 2009 talk I described as 'teenage nymphette twins'. I mention this not to be sensational but because this is apparently just what Schrödinger was like. He was not a man who thought there were many questions a serious mind should refuse to ask.

Which made it particularly galling to him, professionally, that the theory he’d written in that Swiss chalet was being used to argue that an entire class of questions about physical reality were simply off the table. That the universe described by his equation existed, in full, only when someone looked at it.

He thought that was insane. And he designed a thought experiment to say so.

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The thought experiment goes like this.

Take a cat. Place it in a sealed box with a radioactive atom, a radiation detector, and a flask of poison wired to the detector. If the atom decays, the detector fires, the mechanism breaks the flask, the cat dies. If not, the cat lives.

Quantum mechanics says the atom, until observed, exists in a superposition: simultaneously decayed and not decayed. Not because we don't know which; because it genuinely has no definite state until measured. Which means the cat, until you open the box, is also in superposition. Simultaneously alive and dead.

Schrödinger's point was that this is clearly absolutely ridiculous, and that any theory producing this conclusion cannot be a complete description of reality. He meant it as a critique. The textbooks turned it into a feature.

The photograph, incidentally, is the actual cat from my Cambridge lecture: a tiger, in superposition, simultaneously present and fading. And in the corner of the slide is the actual title of that lecture, which I'm going to read to you in full: 'The return of pilot waves; or, why Bohr, Heisenberg, Pauli, Born, Schrödinger, Oppenheimer, Feynman, Wheeler, von Neumann and Einstein were all wrong about quantum mechanics.' I never won a Nobel Prize in physics during my years as a theoretical physicist. But I believe, with all humility, that I deserved one for Most Provocative and Heretical Title for a Physics Lecture. Saying that sort of thing in a physics department is normally the kind of thing that gets you put up against a wall and shot, never mind what it does to your career. Somehow I got away with it. By the end of tonight you can judge for yourselves whether the title was justified.

And while I was at Cambridge being heretical, I extended the thought experiment myself, along the lines of an argument called "Wigner's friend". Forget the cat. Replace it with a person - I chose one of the teenage nymphette twins - since we'd just been talking about Ithi and Withi. According to strict Copenhagen logic, before you open the box she's in a superposition of having found one result and having found the other. A superposition of mental states. Of conscious experiences.

In keeping with the cat theme I was going to call the experiment "Schrödinger's Pussy", but even in 2009 the creeping tentacles of the newly woke HR departments were beginning to loom, Benny Hill had already been cancelled, and people were going around screening for double entendres. So as I wasn't sure I would get away with it, I called the experiment Schrödinger's Woman instead, on grounds of discretion I am no longer sure I endorse.

The point, whatever you call it, is serious. If quantum superposition applies universally, as the theory insists it must, then either it stops somewhere, at some scale, for some reason the theory cannot specify, or observers themselves are entangled with the systems they measure. The observer and the observed are not cleanly separable.

Which is a problem. Or a discovery. Depending on which mode of attention you bring to it.

9

Before we leave the cat, the definitive treatment of the measurement problem, from the cartoonist Stephen Notley drawing the adventures of Bob the Angry Flower. I showed this at Cambridge in 2009 and they seemed to enjoy it. [Let them read the strip. Do not read it aloud.] Notice that the flower is a strict Copenhagenist right up to the moment he wants his beer. Everyone is. Nobody has ever opened a fridge to collapse a superposition of beers; you open it to find out what is in there. Hold on to that instinct. It is that of Louis de Broglie, and we are about to watch a room full of the cleverest people who ever lived talk him out of it.

By the way there is a panel on that cartoon which should have had me carted away in manacles by the HR police, which no-one seemed to notice at the time, so I think I got away with it. And yes, it is the last one!

4. THE SOLVAY CONFERENCE & THE PLAY

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Two years after Schrödinger wrote his equation in the Alps, the most important gathering of physicists in the twentieth century took place in a lecture hall in Brussels.

The Solvay Conferences were funded by a Belgian industrialist who believed in science and had enough money to bring everyone who mattered to one place once every few years. The 1927 conference had twenty-nine attendees. Seventeen of them either had already won the Nobel Prize or would. Marie Curie was in the room. Einstein was in the room. Bohr, Heisenberg, Max Born, Schrödinger, Pauli, Dirac: all the legends in the room. That photograph is them, and it is the most photographed group of physicists in history. You can count them.

And in that room, a thirty-five year old French aristocrat named Louis de Broglie stood up and presented a theory that, had it been taken seriously, would have resolved the measurement problem, explained the two-slit experiment without paradox, and removed the need for Schrödinger's Cat entirely.

It was not taken seriously.

What happened next split into two possible histories. One of them we could have had. One of them we got. And we are going to dramatise both.

I'm going to need six volunteers.

11

Before I cast anyone, you should meet the opposition. Four faces. Learn them now, and the play will make a great deal more sense.

At the top: Niels Bohr. The father figure, and not just in manner: he was fifteen years older than the three young men around him, and every one of them at some point passed through his Institute in Copenhagen, which is why the orthodoxy that is insisted on is called the Copenhagen interpretation. It is named after his address. Two things to know about Bohr. First, for a great theoretical physicist he was remarkably uncomfortable with serious mathematics. The calculating was always done by somebody else: the family mathematician was his younger brother Harald, and there was a lifelong procession of brilliant young assistants taking dictation while Bohr paced up and down, drafting and redrafting, sentence by agonised sentence. What Bohr supplied was words. Which brings us to the second thing: the words amounted to a philosophy, borrowed in large part from a movement called 'logical positivism' fashionable in the 1920s, the doctrine that a statement about anything that is not observable is not merely unknowable but meaningless. Philosophy gave that idea up generations ago, on the very practical and reasonable basis that it's total bollocks. It survives to this day in physics departments, embalmed inside the interpretation that bears his city's name. Perhaps philosophers are more sensible than physicists.

On the left: Werner Heisenberg. Bohr's brilliant lieutenant. In 1925, aged twenty-three, on a bare island in the North Sea, he invented the first working version of quantum mechanics: matrix mechanics, all algebra and no picture, and he liked it that way. Schrödinger's wave equation arrived a few months later, gave the same answers, was far easier to use, and Heisenberg never entirely forgave him. The uncertainty principle is his. So, in the play you are about to watch, is the threatening. During the Second World War, Hitler put him in charge of the German effort to develop the atomic bomb. Yep, Nazis with nuclear weapons, what joy. Of course we know they failed to make it work before Oppenheimer and Feynman and the rest of the clever people in the Manhattan project at Los Alamos. Some people believe Heisenberg failed to make it work on purpose. Other people aren't so sure. This was the subject of a theatre play 'Copenhagen' by Michael Frayn which I remember going to see in London years ago.

On the right: Wolfgang Pauli. The attack dog. Colleagues called him the conscience of physics, which meant that he told everyone, precisely and witheringly, exactly why they were wrong. His most famous verdict on a paper he disliked: it is not even wrong: *nicht einmal falsch*. The Pauli exclusion principle is his: no two electrons in the same state. File that one away. Later this evening it will be holding up a dying star, and I will tell you what the textbooks won't about how.

And at the bottom: Paul Dirac. The strangest, and quite possibly the deepest, of them all. His equation married quantum mechanics to special relativity and conjured antimatter out of pure algebra before anyone had seen a single particle of it. He almost never spoke: his Cambridge colleagues defined a unit, the dirac, of one word per hour. Today we would probably say he was autistic; his biographer thinks so. In the play we're about to perform, Dirac gets no lines. This is historically accurate.

These four, plus Einstein, who thought they were all wrong but mostly held his fire, are what a polite thirty-five-year-old French aristocrat is about to stand up in front of.

Now. Six volunteers.

12

Cast your six volunteers from the audience. Read each card aloud while indicating the person you’ve chosen for it: the laughter at casting is part of the function; it relaxes the room before the philosophical content arrives.

> **MR. DE BROGLIE**: French. Highly intelligent. Masterful speaker. I'll be him.. **MR. PAULI**: Humourless Austrian. Ernst Stavro Blofeld. You are always right and you know it. That can be Nye. **MR. EINSTEIN**: German. Warm. Avuncular. Everyone loves you. You sound continuously amused. **MR. SCHRÖDINGER**: Massively upper-class Austrian Anglican priest. Secret pervert. **MR. BOHR**: Danish. Prissy. Pernickety. Hopelessly sad. **MR. HEISENBERG**: German

equivalent of a Cockney gangster. A Nazi Ray Winstone. You are about to threaten someone. **MR. BRAGG**: Posh English. Sits next to Heisenberg. Unwise. **THE SOLVAY AUDIENCE**: Everyone else. Follow stage directions.

I would cast one of the girls as Madame Curie but she has no function other than to die horribly of aplastic anaemia in a few years because she was unfortunate to discover radioactivity before anyone realized it was dangerous. So let's not.

Please exaggerate all foreign accents, including your own if you happen to have one. That’s not optional.

Brief the volunteers: this time there are lines, and you will get each of yours from me as we go; your only job is the delivery, bigger than feels reasonable. We are going to perform this conference twice. First: the universe we could have had.

13

The 1927 Solvay Conference. Enthusiastic applause. Intermittent whooping from near the back of the hall. Mr. Bohr is sitting in the centre of the front row. He applauds and flashes a beaming smile at Mr. de Broglie. However there appears to be something wrong with his eyes.

MR. DE BROGLIE: … and so we conclude that the dualist representation by corpuscles and associated waves allows us now to see the non-relativistic quantum theory as just statistical mechanics with a different (quantum) dynamics. And with that, gentlemen, Madame Curie, I end my presentation. I thank you for your attention.

MR. PAULI: My dear de Broglie, I should, I think, like to congratulate you. Since I read your very sharp article in the Journal de Physique I have been intrigued by this approach. With your apparently successful extension to the many-body case I begin now to see that much of what we have thought up to now is nicht einmal falsch: not even wrong. I even see how some doubts I had about inelastic scattering could be resolved. Working alone in Paris away from our little circle has been good for you it seems. [He nods in the direction of Mr. de Broglie and sits down.]

Mr. Heisenberg leans against one of the walls of the lecture theatre, smoking a cheroot. He does not smile or clap. His eyes are fixed on the back of Pauli’s neck. A thin hiss of smoke escapes from his delicately pursed mouth.

MR. BOHR: … so I shall try to describe to you a certain general point of view, which I hope will be helpful in order to harmonize the apparently conflicting views… I call it [offstage, a trumpet sounds] the ‘Complementarity Principle.’ It says, you see, that with there being this dual wave-particle nature of reality there is, we must all now agree, no logical picture that can simultaneously describe and be used to reason about all properties of a quantum system. [General hilarity, then silence broken by occasional embarrassed coughing.]

MR. EINSTEIN: But my dear Bohr, is that not precisely what M. de Broglie has provided? It is, if I may say, now generally accepted that the de Broglian mechanics has lifted a corner of the Great Veil.

MR. HEISENBERG: Seen one of these so-called ‘electrons’ when you’re not looking at it, have you? Eh? [Bragg foolishly calls out ‘Yes, indeed!’. Heisenberg lunges at him, but is restrained by Mr. Dirac.]

MR. SCHRÖDINGER: What madness is this? These conflicts Bohr speaks of are in your head and his. You would replace de Broglie’s beautiful, logical, comprehensible quantum theory (which so elegantly extends the theory of poor Boltzmann and Mr. Einstein) with such pettifogging mumbo-jumbo? This would lead us down the road to rats being at the same time both dead and alive…

MR. BOHR: But… I am the Father of Quantum Mechanics. I have an Institute. You must listen to me…

ALL: Father of My Arse, mate. Hoo, hoo. Get back to Copenhagen… You belong in an Institute. Etc.

Enter men in white coats. Bohr and Heisenberg are put into straitjackets and dragged away.

MR. HEISENBERG: [offstage] But to hope for so-called hidden variables is like saying 2+2=5. OOoofff!

Soon afterwards, inspired by the physicists and instead of waiting until the 1960s as expected, the philosophers have all the logical positivists taken outside and shot. All the old problems in philosophy are opened again, and everyone has much more fun. Henceforth, quantum theorists are seen by the public (if seen at all) as rather dull on account of the lack of barking paradoxes. At least until Marie Curie discovers nonlocality in 1935…

MIKE: ‘But that is not the universe we live in. Shall we find out what actually happened?’

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The 1927 Solvay Conference. Polite applause. Some photon somewhere goes the other way.

MR. DE BROGLIE: … and so we conclude that the dualist representation by corpuscles and associated waves allows us now to see the non-relativistic quantum theory as just statistical mechanics with a different (quantum) dynamics. And with that, gentlemen, Madame Curie, I end my presentation. I thank you for your attention.

MR. PAULI: It seems to me that, concerning the statistical results of scattering experiments, the conception of Mr. de Broglie is in full agreement with Born’s theory in the case of elastic collisions, but that it is no longer so when one also considers inelastic collisions. I should like to illustrate this by the example of the rotator… [there follows a technical argument…] … Mr. de Broglie’s point of view does not then seem to me compatible with the requirement of the postulate of the quantum theory, that the rotator is in a stationary state both before and after the collision.

MR. DE BROGLIE: [falters; concedes the point is not yet fully resolved; looks uncertain]

MIKE: ‘The vote: who supports de Broglie’s pilot wave?’

Only Einstein, and perhaps Schrödinger, raises a hand.

MIKE: ‘Copenhagen it is.’

Return the volunteers to their seats, with applause. Then the tonal shift: from comedy into genuine historical regret. Don’t rush it.

That is what actually happened. Polite applause. Pauli's quote is authentic. A technical objection that, as Bell later showed, was actually incorrect. A reply from de Broglie that I didn’t include in full - it contained the essential answer but wasn’t recognised as such. And a theory that could have clarified everything, dropped (not refuted, dropped) because the room was moving in a different direction and the momentum of the Copenhagen interpretation was already too great to resist. Because Bohr and his teenage logical positivism had acquired just too much influence.

De Broglie gave up his own theory by 1930. He spent twenty-two years telling his students that hidden variables - that is, particles having properties when you’re not looking at them - were impossible. He had proved the opposite.

5. COPENHAGEN CRITIQUE & BELL PIVOT

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So what did the Copenhagen interpretation, the theory that won the argument in that Brussels lecture hall, actually say?

Five claims. I’ll state them plainly.

One: a quantum system is completely described by its wave function, which represents the observer’s knowledge of the system, or its potentiality (whatever you mean by that). Between measurements, this is all there is. You'll remember at the start that I said that physicists make a mathematical model of the universe, and they map the mathematical objects that appear in the equations onto real things that apparently exist. So notice what they're doing here.. They're saying the wave function doesn't represent anything real, it represents an abstract concept: knowledge. So you open the box. You see the cat lying on its back with some digusting foam coming out of its mouth. It is dead. It is deceased. It is an ex-cat. And your knowledge instantly increases, and the state of the system instantly stops evolving according to the Schrödinger equation and does something else instead. You've got to admit that in what's supposed to be a mathematical model of the universe, that's a damned weird thing to do. I mean, whose knowledge? And do fruit flies count?

Two: nature is fundamentally probabilistic. When a measurement occurs, the wave function collapses, randomly, to one definite outcome. This collapse is not a physical process the theory describes. It simply happens.

Three: the uncertainty principle is not about the limits of our instruments. Particles genuinely do not have simultaneous definite values for position and momentum. The indeterminacy is in nature, not in us.

Four: there is no logical picture that can simultaneously describe all the properties of a quantum system. Wave and particle are complementary: you can see one or the other depending on what you measure, never both. Don’t ask what the system is when you’re not looking. The question has no meaning.

Five: measuring devices are classical. The quantum world ends somewhere. Don’t ask where.

Now, this framework works. Industrially, spectacularly, without exception in its domain. Every transistor in every device in this room is a Copenhagen success story. I am not telling you it’s wrong in its predictions.

What I am telling you is what Schrödinger told you: that as a philosophical account of reality, it is, in his exact words, a philosophical extravaganza dictated by despair. It is a theory that elevated its own incompleteness into a principle. That looked at the questions it couldn’t answer and declared them unaskable. That built a wall around its own ignorance and called the wall a discovery.

You have seen this move before. Casaubon in 1614 didn't prove the Hermetic ideas were wrong. He proved the historical claim was mistaken, and used that to rule the questions out of court. Bohr in 1927 didn't prove that particles don't have trajectories. He decided the question wasn't worth asking, and then made sure, as best he could, that nobody else asked it either.

One more thing before we meet the chorus of impossibility. Let me state something plainly. If quantum mechanics as it stands is complete, if there really is nothing underneath the wave function, then there are exactly three positions available to you. One: the wave function, and only the wave function, exists. You, this room, your dinner: all of it just wave function. but the Copenhagenists say that isn't true, the wave function represents knowledge. Two: solipsism. Only your own mental processes exist. If that's true then there really is no point to anything. Three: there is something underneath the wave function after all: the particles have properties the textbooks haven't told you about. Hidden variables. No-one believes the first two. So. Everyone believes in hidden variables, don't they. Congratulations. Until about 1990, holding that opinion out loud would have ended your career in physics.

16

What followed the Solvay Conference in Brussels was one of the most sustained exercises in collective intellectual self-deception in the history of science. A partial list.

Heisenberg: the idea of particles existing independently of observation is impossible. Born: any future deterministic theory cannot be a modification of the present one: how this could happen without sacrificing well-established results, he leaves to the determinists to worry about. Wheeler: every attempt to defend hidden variables has been struck down. Landau and Lifshitz (authors of the most widely used graduate physics textbook of the twentieth century) stated flatly that in quantum mechanics there is no such concept as the path of a particle. Feynman: nobody knows what machinery produces the interference pattern.

And then there is Heisenberg again, at his most confident: to hope for hidden variables, he said, is as ridiculous as hoping that two times two equals five.

To cap it all, John von Neumann (the most formidable mathematician of the twentieth century, the man who designed the architecture every computer you have ever used is based on) published a mathematical proof that hidden variables were impossible. Not unlikely. Not unproven. Impossible, in principle, by rigorous mathematics.

Oppenheimer, at Princeton, made the position clear when Bohm published his 1952 paper resurrecting pilot wave theory. He didn't engage with it. He said: we consider it juvenile deviationism. We don't waste our time actually reading the paper. If we cannot disprove Bohm, then we must agree to ignore him.

Princeton colleagues were less restrained. Bohm was called a public nuisance. A Trotskyite. A traitor. He was exiled (not metaphorically, exiled) to Brazil.

Nobel prize winner Murray Gell-Mann, thirty years later, put the opposition belief simply. Bohr, he said, had brainwashed a whole generation of physicists into believing the problem had been solved.

Every name on that list was wrong. Not about the predictions, about the impossibility. Hence the provocative title of my 2009 talk.

17

Von Neumann’s proof deserves its own moment, because it was the intellectual foundation on which everything else rested. If the greatest mathematician alive had proved, rigorously, mathematically, that the kind of theory de Broglie was proposing was impossible in principle, then there was nothing to discuss.

Except the proof was wrong.

Not subtly wrong. Not wrong in a way that required years of careful analysis to detect. Wrong in a way that, once pointed out, is obvious. The proof assumed, in a critical step, precisely the thing it was supposed to be proving. It was circular, dressed in enough mathematical formalism that nobody noticed, or nobody who noticed was listened to.

The person who noticed was a German philosopher named Grete Hermann. She published the refutation in 1935: eight years after the Solvay conference, three years after von Neumann’s proof appeared, and at a point when the Copenhagen interpretation had already hardened into something close to orthodoxy. Her paper was ignored. Not refuted. Not even engaged with. Ignored.

It was left to John Bell to rediscover the same flaw, independently, in 1966. Thirty-one years later.

I want to sit with that for a moment. Thirty-one years. The foundational proof underpinning the impossibility of a whole class of theories contained a logical fallacy that had been correctly identified in print, by a careful thinker, in 1935, and the field simply did not notice, or did not want to notice, for three decades. The questions were not just declared out of order. The paperwork proving they were out of order turned out to have been forged.

That said, von Neumann was a terrifying genius and a fascinating man. His biography - *The Man from the Future* - is in the Academy library.

18

Grete Hermann is not a name that appears in most physics textbooks. She was a mathematician and neo-Kantian philosopher who studied under Emmy Noether, herself one of the most significant mathematicians of the twentieth century and another woman whose work was systematically undervalued by the institutions around her. Hermann published her refutation of von Neumann’s proof in a philosophy of science journal in 1935. She moved on to other things. The physics community continued citing von Neumann as though she hadn’t written a word.

I am not suggesting this happened because she was a woman, though that is not obviously irrelevant. I am suggesting it happened because the Copenhagen interpretation had by 1935 acquired the social and institutional weight of a consensus, and consensus, in science as in other human endeavours - hello climate change, leftist politics - has a way of not noticing things that would complicate it.

You met this pattern last time. The Gnostic tradition, correctly identifying problems with official theology, went underground. The Corpus Hermeticum, carrying two thousand years of accumulated intuition about the nature of consciousness, went underground. Boehme, independently arriving at the same cosmological structure as Plotinus without ever having read him, was suppressed by his local pastor inside a week.

Hermann didn’t go underground: she moved on to moral philosophy and resistance politics, which in 1935 Germany - with Hitler already Chancellor - was a more pressing problem. But her finding went underground without her.

What was buried with it was thirty years of physics in which the foundational question (do particles have definite properties when no one is looking at them?) was not merely unanswered but undiscussable. The wall held.

Until Bell.

19

> *“In 1952 I saw the impossible done. It was in papers by David Bohm. Bohm showed explicitly how parameters could indeed be introduced into nonrelativistic wave mechanics, with the help of which the indeterministic description could be transformed into a deterministic one. More importantly, in my opinion, the subjectivity of the orthodox version, the necessary reference to the ‘observer,’ could be eliminated.*
>
> *But why then had Born not told me of this ‘pilot wave’? If only to point out what was wrong with it? Why is the pilot wave picture ignored in text books? Should it not be taught, not as the only way, but as an antidote to the prevailing complacency? To show us that vagueness, subjectivity, and indeterminism, are not forced on us by experimental facts, but by deliberate theoretical choice?”*
>
> John Bell, *Speakable and Unspeakable in Quantum Mechanics*, 1987

Read the quote in full. Slowly.

It's important to realize though that what Bohm had done was essentially just what de Broglie had done in 1927, though he defined what was going on in a measurement process a bit more carefully. This wasn't realized because people mistakenly thought that de Broglie had only done a simple theory that worked only for one particle, when he had done the fully general theory for as many particles as you like. One of the reasons for this was that the proceedings of the Solvay conference were only ever published in French and were just gathering dust, unread, in a few libraries. Then Antony Valentini - of whom more later - and his friend Guido Bacciagaluppi published a full English translation with commentary in 2009, and it became clear that de Broglie had accomplished much more than was generally thought. Bohm and his later collaborators were strangely reluctant to give him any credit, as far as I can tell because he just wasn't interested in academic questions of priority.

20

John Bell has an interesting quote you can read on the slide. Another similar one is as follows:

> *"Many older physicists get really angry about this and clearly will never overcome the dominant thought patterns of the prevailing paradigm of orthodox quantum theory. Sadly, it will almost certainly be necessary to wait for them all to die."*
>
> John Bell

Bell was not known for extravagant statements. He was a precise, careful, somewhat reserved Irish physicist who spent his career at CERN - the particle physics laboratory in Switzerland - and did not often editorialise. Which makes this sentence, written about colleagues who refused to engage seriously with the evidence for quantum realism, the more striking.

It is also a sentence you have heard before. Not in those words, but Casaubon's proof in 1614 closed a question by discrediting its historical credentials rather than engaging its philosophical content. Copenhagen closed a question by declaring it meaningless rather than answering it. In both cases, the people asking the questions didn't stop asking them. They were outlasted, suppressed, or exiled to Brazil.

The questions did not go away. They went underground, and resurfaced, as they always do, when the generation that had declared them impossible was no longer in the room.

Bohm published in 1952. Bell vindicated the approach in 1966. And the pictures (the actual, calculated paths of particles in a pilot-wave universe, some of the most striking images in modern physics) had been drawable, in principle, since 1927. You will see them in a few minutes.

But first I want to show you exactly how large the heresy is. It is one word long.

6. PILOT WAVE THEORY & THE PAYOFF

21

Everything you have ever heard about the weirdness of quantum mechanics (the cat, the collapse, reality depending on the observer) hangs on one word.

In the textbooks, the central quantity of the theory (the square of the wave function, $|\Psi|^2$) is defined as the probability of *finding* the electron at a given place, if you perform a suitable measurement. Read that definition again and notice what it smuggles in. Measurement is built into the foundations. The theory is, from the ground up, a theory about experiments: about what happens when somebody looks.

De Broglie's move (the whole heresy, the thing that emptied the room in Brussels) is to change that word. It is not the probability of *finding* the electron there. It is the probability of the electron *being* there. Full stop. No measurement required. No observer. The electron is somewhere whether you look or not, and the mathematics tells you how likely each somewhere is.

Change that one word and the entire character of the theory changes with it. Quantum mechanics stops being a theory about measurements and becomes a theory about what matter does: a dynamical theory of particles moving along trajectories, squarely in the tradition of Newton, with one addition.

At Cambridge in 2009 I had a slide at this point titled ‘Atoms with Newtonian trajectories: a surprising observation,’ and it caused more consternation than anything else in the talk. You remember Newton's laws; you learned them at school. F=ma, force = mass times acceleration and all that. What my slide showed was this. Take ordinary classical mechanics (the statistical mechanics of Newtonian particles, written in a particular less well-known standard form), merge it with a standard mathematical constraint that the sum of probabilities over all space has to be equal to one and stay that way as time passes, and out pops the Schrödinger equation. The exact equation of quantum mechanics. With one extra term: an additional potential, amounting to an extra force. And it runs just as cleanly the other way: subtract that one term from quantum mechanics, and classical mechanics falls out. That is the entire distance between Newton’s world and the quantum world. One force. And hardly any physicists seem to be aware of this.

I won’t do the algebra tonight: you’re not maths students, and I promised. But hold on to the physical content, because the rest of the evening depends on it. That extra force is proportional to the local curvature of the pilot wave field. Where the wave bends sharply, the push is strong. The pilot wave field is not a bookkeeping device and not a wave of probability. It is a causal agent. It pushes matter around. In a few minutes I’m going to show you it holding up a star.

22

So here is what de Broglie proposed in 1927, and what Bohm independently reconstructed in 1952, and what the establishment spent thirty years insisting was impossible.

Is it a wave or is it a particle? Both. Both exist. That’s it. That’s the whole move.

A particle (an electron, a photon, whatever you’re tracking) is a real, localised thing with a definite position at all times, whether or not anyone is looking at it. It is not a superposition. It is not a smear of probability. It is somewhere. And simultaneously, a pilot wave field (real, physical, propagating through space) exists alongside it and guides its motion. The wave is not the particle. The particle is not the wave. They are two distinct physical entities, and together they constitute the complete description of the system.

Now apply this to the two-slit experiment. The particle goes through one slit: always, as common sense demands. But the pilot wave field goes through both, interferes with itself on the other side, and the interference pattern that develops in the wave produces a corresponding pattern in the trajectories the particle is guided along. The particle never goes where the waves cancel out. It accumulates where they reinforce. Fire enough particles and you get an interference pattern on the screen: not because each particle is in two places at once, but because each particle is guided by a field that was.

The mystery is gone. Not explained away: explained. There is no measurement problem, because the particle always has a definite position. There is no wave collapse, because the wave is a real field obeying Schrödinger’s equation continuously. There is no special role for the observer, because observation doesn’t create the outcome: it simply reveals what was already there.

This is what the second mode of attention produces when it’s applied to quantum mechanics. Not a calculator. A picture.

23

Before the theory earns its keep, look at the real thing. This is not a simulation. This is the double-slit experiment performed with actual electrons (fired one at a time, each arrival recorded) and the frames run from a handful of electrons to tens of thousands.

Look at the early frames first. Each electron arrives as a single dot. One localised flash, at one place, on one detector. Nothing wavelike about it whatsoever. And the dots look random: a spatter, no structure at all.

Now let the frames accumulate. Out of that apparently structureless rain of individual dots, the fringes emerge. Bands where electrons pile up; bands where none ever lands. The interference pattern, assembled one definite particle at a time, by particles that never met each other.

This is the thing Feynman said contained the whole mystery, and you can see why. Each electron arrives like a particle: a dot. The pattern they build collectively belongs to a wave. If the only two options in your head are the ones common sense offers (it's a particle, or it's a wave) then this picture is impossible, and the honest response is Feynman's: nobody knows what machinery produces it.

But you have just been given a third option. Each dot is a particle that went through one slit. The pilot wave field went through both. And if that's true, it ought to be possible to calculate the actual paths (every trajectory, from source to screen) and watch the fringes assemble themselves for a reason. It is possible. Somebody finally did it.

24

What you're looking at are the calculated trajectories of particles in a pilot-wave universe passing through a double slit: the theory's answer to the frames you've just seen. B and B' are the two slits. Each line is the path of a single particle, guided by the pilot wave field.

Notice two things. First: every particle goes through one slit. The trajectories are definite, continuous, and they never cross. There is no superposition. No paradox. Second: the distribution of where those particles end up, after being guided by the interference pattern in the wave, is precisely the quantum mechanical prediction: the same pattern the Copenhagen interpretation can only describe statistically, with no explanation for why any individual particle lands where it does.

Pilot-wave theory gives you this. Individual trajectories, fully determined, fully consistent with every prediction quantum mechanics makes, and a picture of what is actually happening.

This calculation was published by Philippidis, Dewdney and Basil Hiley in 1979: remember Hiley's name, because in a few minutes you will find him in a photograph, standing outside the front door of this building. The calculation can be done on an undergraduate computer. The tools to draw these lines had existed, in principle, since 1927: more than half a century in which nobody drew them, because the dominant interpretation had declared the lines didn't exist.

I showed these to my Cambridge audience in 2009 and the reaction was always the same. A kind of quiet. The sense of something being restored that should never have been taken away.

25

Now the promise I made a few minutes ago. I said the pilot wave field is a causal agent: that it pushes matter around. Here is the demonstration, and it is sitting in the sky.

A star like our sun eventually runs out of fuel. Nuclear fusion stops. Nothing is burning at the core any more, nothing is pushing outward, and gravity, which has been waiting patiently for ten billion years, starts to crush it. And then, at about the size of the Earth, the collapse stops. The star settles down as a white dwarf and sits there, stable, for billions of years. Something is holding it up against the gravity of an entire star's worth of matter.

Here's the quiz. The textbooks tell you there are four fundamental forces of nature. Which one is doing it? Gravity? Gravity is the one trying to kill it. Electromagnetism? No, the star's matter is electrically neutral overall, and electromagnetic pressure is nowhere near strong enough in any case. The weak nuclear force? No. The strong nuclear force? No.

The textbook answer is 'electron degeneracy pressure', which is a name, not an explanation. Press the textbook, ask which force produces this pressure, and it goes quiet, or mutters something about the Pauli exclusion principle. Which is also a name.

In pilot-wave theory the answer is simple, explicit, and quantitative. It is the quantum force: the push of the pilot wave field, the same extra term we met three slides ago, proportional to the curvature of the wave. It appears all over physics under assumed names: Pauli repulsion, exchange forces, degeneracy pressure. Antony Valentini (you will meet him properly in a few minutes, in a photograph taken outside this building) calls the pilot wave field a new type of causal agent in the history of physics.

The pilot wave field holds up stars. Hold that thought for the rest of the evening: whatever else it turns out to be, it is not a metaphor.

26

I want to tell you about a positron called Priscilla.

Hans Dehmelt spent decades carrying out extraordinarily precise experiments on individual subatomic particles, capturing them in electromagnetic traps and studying them in isolation. In 1987 he held a single positron in a trap for three months. (A positron is just an electron that is positively charged rather than negatively charged). Because free positrons don't persist in ordinary matter (they meet an electron and annihilate almost instantly), the particular positron under study had no opportunity to be swapped for a different one. He knew he was looking at the same particle, continuously, for three months.

He measured its magnetic moment to twelve decimal places. He gave it a name. He called her Priscilla.

I tell you this because in 1928, one year after the Solvay conference, Bohr and Pauli and others had published a rigorous argument that the magnetic moment of a free electron could never be observed. The argument was still being defended, in print, as late as 1985. Today the magnetic moment of the electron is arguably the best-measured number in all of science.

Dehmelt's Nobel lecture ends with a thought that Bohr would have found unintelligible: he suggests that the well-defined identity of an elementary particle (the fact that Priscilla is Priscilla and not some other positron) is something fundamentally new that deserves recognition. So he named her. As you would a pet.

The Copenhagenists said quantum entities were not the sort of thing that could be isolated, observed continuously, or given names. Dehmelt did all three, and won the Nobel Prize for it.

The moral I drew from Priscilla at Cambridge, and I stand by it: be modest about the philosophical implications of your theories, and never, ever underestimate the cleverness of experimentalists.

27

Dehmelt also trapped a single barium atom (strictly speaking an ion but some of you might not know what that is) which he kept floating in a tiny ion-trap vacuum chamber for ten months. Under suitable conditions of laser stimulation, she became visible to the naked eye. He called her Astrid.

It used to be claimed that no-one could see an atom with the naked eye. The argument seemed reasonable: atoms are very small, therefore invisible. The mistake, as Dehmelt pointed out, is assuming that smallness is the important variable. What actually matters is brightness and isolation from other atoms. A laser-stimulated barium atom produces a hundred million photons per second; your eyes can collect several thousand of them. The normal retina responds to even a few photons, so you see the atom, exactly as you'd see a distant star or any other bright, isolated object. (Or nuclear disintegrations in my missing 1910 spinthariscope containing deadly radioactive polonium. I hope whoever took it doesn't put it on their breakfast cereal..)

Astrid is visible because she is alone and lit. Which is, when you think about it, what visibility has always required.

I mention this alongside Priscilla because together they make a point the trajectory pictures make formally: the quantum world is not a world of irreducible mystery where observation destroys what it observes and individual entities cannot be tracked or named. That picture was a philosophical choice, not a physical discovery. The entities are real, they persist, they have identities, they can be watched. People have manipulated individual atoms on surfaces so that they spell out words. The old arguments are done.

What you cannot do, within the Copenhagen framework, is say any of that out loud in a physics department without someone giving you a look.

7. BELL'S THEOREM & DAVID BOHM

28

There is one more result I need to give you before we meet the man who followed these ideas to their philosophical conclusion. It comes from John Bell again, and it's the most important finding in quantum foundations since the Solvay conference.

In 1964 Bell asked a precise mathematical question: is it possible, even in principle, for a theory with hidden variables (particles with definite properties when no-one is looking) to reproduce all the predictions of quantum mechanics, if those hidden variables are local? That is, if each particle carries its own information and is only directly influenced by things in its immediate vicinity?

The answer he proved is no. He derived an inequality, a mathematical constraint, that any local hidden variable theory must satisfy. And he showed that quantum mechanics, in certain experiments, predicts violations of that inequality.

The experiments were done. Beginning with Alain Aspect in 1982 and confirmed many times since with increasing precision, the results are unambiguous: Bell’s inequality is violated. Nature does not satisfy it. Which means nature is not local.

Let me be careful about what this means and what it doesn’t. It does not mean you can send information faster than light. What it means is that there are real physical correlations between distant events that cannot be explained by anything either event was carrying with it when they separated. The universe has connections (genuine, irreducible, non-local connections) that no picture of isolated particles exchanging local influences can account for.

The pilot-wave theory is explicitly nonlocal: the pilot wave field that guides particles is defined across the whole configuration of the system simultaneously, responding instantly to changes anywhere. Bohm didn’t claim this was a problem. He claimed it was pointing at something. Something deeper than particles. Something that the separateness of particles was, in some sense, a surface appearance of.

29

David Bohm is one of the strangest careers in twentieth-century physics, and one of the most important.

He was a student of Robert Oppenheimer, the same Oppenheimer who would later call Bohm's work juvenile deviationism and have him effectively blacklisted. Before that in the war Oppenheimer wanted Bohm for the Manhattan Project, but he couldn't because General Leslie Groves (played by Matt Damon in the recent Oscar-winning Oppenheimer movie) wouldn't give him a security clearance to work on atomic weapons because he’d just been a bit too lefty at the University of California when he was younger. In those days that was seen as a very bad thing, whereas now it's practically obligatory of course. In 1949, called before the House Un-American Activities Committee on suspicion of Communist sympathies, Bohm refused to testify against his colleagues and invoked the Fifth Amendment. Princeton declined to renew his contract. He was arrested, then acquitted. He left the United States, spent several years in Brazil, then Israel, and eventually settled permanently in London at Birkbeck College, where he spent the rest of his life.

During all of this (the blacklist, the exile, the institutional hostility) he kept working. The 1952 papers that Bell read and described as doing the impossible were written at Princeton in 1951, under the shadow of the subpoena, and published just as he reached Brazil, in what must have been fairly unconducive circumstances for foundational physics research.

By the 1980s his answer to the question Copenhagen had declared unaskable (what is actually happening?) had moved well beyond quantum mechanics, into territory that will be familiar to anyone who saw the last lecture. He had become convinced that the nonlocality Bell confirmed was pointing not to a strange quirk of particle physics but to something about the deep structure of reality itself.

He called it the implicate order.

8. THE VALLICO CONNECTION

30

I want to pause on where you are.

In August 2010, I co-organised what turned out to be the largest conference ever held at this centre: the building you are sitting in right now. We invited essentially every de Broglie-Bohm researcher in the world to Vallico Sotto. And they came.

That is a photograph of most of them, outside the front door. If you look carefully you will find Basil Hiley, Bohm’s closest collaborator for decades, co-author of their book The Undivided Universe, the definitive statement of Bohm’s mature physics, and the man whose 1979 trajectory calculation you were looking at ten minutes ago. Hiley continued developing these ideas until his death last year, and the loss to the field is considerable. You will also find Antony Valentini, who has extended pilot-wave theory into territory that goes beyond anything de Broglie or Bohm originally envisioned: the possibility that in the very early universe, before quantum equilibrium was established, the theory makes predictions that differ measurably from standard quantum mechanics, and that traces of this might be readable in the cosmic microwave background. Valentini’s book on the subject, *Beyond the Quantum*, published by Oxford this year, is in the Academy library. I co-authored a paper with him on quantum non-equilibrium (my only publication in the de Broglie-Bohm field) and I can tell you from personal experience that he is one of the most original physicists currently working on these problems.

You will also find, if you look, Samantha. What you will not find is my daughter Saska, who was five years old at the time, who was absolutely present at this conference, and who had her nose into everything except, apparently, the group photograph. I imagine she has her own explanation for the absence, which I look forward to hearing.

One of the questions we announced in advance for discussion was this: “Why should young people be interested in these ideas, when showing interest in quantum foundations still might harm their careers?”

It was 2010. The answer was not obvious. The chain from Brussels 1927 runs through this building. You are sitting in the church where it happened.

9. THE IMPLICATE ORDER & CONVERGENCE

31

Bohm’s mature position (the one he developed over the three decades following his 1952 papers, in dialogue with Krishnamurti, with Hiley, with Bell, and with the mounting evidence from nonlocality experiments) was that pilot-wave theory was not the destination. It was a signpost.

The pilot-wave framework had established that the pilot wave field is real, that it permeates all of space, that its influence is instantaneous across any distance. Bohm’s question was: if that is what the pilot wave field is, what kind of universe does it imply?

His answer: the separateness of things is not fundamental. The world of distinct, locally interacting objects we ordinarily inhabit (particles, fields, chairs, people) is what he called the explicate order. The unfolded. The surface. And it emerges continuously from, and re-enfolds continuously into, something deeper that is not divided at all. He called that the implicate order. Implicate from the Latin: enfolded. The whole present in each part. Not connected, which implies things that were separate being linked. Undivided. Whole first.

Now. You have heard this argument before. Not from a physicist in London in 1980. From a philosopher in Alexandria in the third century, working from pure metaphysical reasoning. The One, from which all apparent multiplicity overflows without the source being diminished. The world of separate things as the outermost expression of something that is, at its ground, unified. The soul that never fully descended, that remains, at its root, in contact with what it was never actually separated from.

Different century. Different language. The same architecture.

Bohm knew this. He was not unaware of the philosophical tradition his physics had wandered into. He did not claim the equations proved Plotinus right. What he said, carefully, as a physicist, was that the mathematics kept pointing somewhere it wasn't supposed to point, and that the people who had been there before him, arriving by completely different routes, had left reasonably detailed maps.

32

One more step before I hand the physics over to the philosophers, and it is the step this whole evening has been building towards. The implicate order is Bohm's philosophical framework. What I want to show you now is the piece of plain mathematics that sits underneath it.

Everything I have shown you tonight, I have shown you one particle at a time. One electron, one pilot wave field, one trajectory. But the theory doesn't stop there, and the mathematics is completely explicit about where it does stop. When two systems interact, their pilot wave fields do not stay separate: they join, into a single wave for the pair. Let systems keep interacting (and everything, everywhere, has been interacting since the beginning) and you arrive at the conclusion the formalism forces on you. Strictly speaking, there is one wave function. For the universe. One field. Every particle in this room (the particles in the walls, the particles in the hillside under this building, the particles in you) guided by the same single, undivided object.

So what makes anything separate? You from me, this instrument from that one, one atom from another? In this theory, separateness is a partition. Under certain conditions the one field factorises: it splits, mathematically, into pieces that evolve as though the other pieces weren't there. Walled off from each other. Effectively independent. The pieces are many. The field, underneath, remains one.

One thing becoming many without ceasing to be one. Where have you heard that before? [pause] Plotinus. The One overflowing into the many, each thing a partial descent from a prior unity: that was last time, and it was written seventeen centuries before Schrödinger went up the mountain at Arosa. I am not telling you these are the same claim. I am telling you they have exactly the same shape, and that neither party knew the other existed.

Now the caveat, because I promised you honesty and this is where it earns its keep. I am not claiming this is proven. I am not even claiming it is fully well-defined: there are serious technical objections, and if anyone wants them I will happily ruin the rest of your evening in the bar. What I am claiming is that the question is real. And that it was declared unaskable, for seventy years, by people who, as you have watched all evening, were wrong about nearly everything else in this story.

One more thought to take home, and then I'll let the physicist stand down. Take this picture seriously, just for a moment, and ask yourself: assuming that the field is in some way conscious - big leap! - what would it be like to be that undivided field? Before any partition. No boundaries. No outside. Nothing to contrast with anything. No before, and no after. What would that feel like?

Think about it. Don't answer tonight. Next time I'm going to suggest an answer, and I warn you now, it will also turn out to be an answer to the question of what time is.

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Bohm did not develop these ideas alone. From the early 1960s until Krishnamurti's death in 1986, the two men met regularly and conducted what became one of the most unusual intellectual friendships of the twentieth century: a physicist and a philosopher talking, across three decades, about the nature of thought, the fragmentation of consciousness, and whether a mind trained to divide and categorise could ever perceive the wholeness the physics was pointing at.

Krishnamurti is worth a moment. He was born in South India in 1895, and as a child was identified by the Theosophical Society (the organisation Helena Blavatsky had founded in New York twenty years earlier) as the vehicle for a coming World Teacher. He was educated, groomed, placed at the centre of an international religious movement. And then, in 1929, at the age of thirty-four, he stood up in front of three thousand people who had come to witness his coronation as a spiritual leader, and he declined to do so, dissolved the organisation built around him, and spent the rest of his life saying, with remarkable consistency, one thing.

Thought cannot reach the truth. Because thought is itself the problem.

The analytical, dividing, categorising mind (the mind that separates the thinker from the thought, the observer from the observed, the self from the world) is exactly the instrument that cannot perceive wholeness. Not because it is weak or untrained. Because its primary operation is division. You cannot see the whole by cutting it into pieces and examining each piece. The instrument and the thing it's trying to see are mutually exclusive.

Bohm recognised in this a philosophical articulation of what the physics had been showing him. The implicate order cannot be grasped by the analytical mind for precisely the same reason a net cannot catch water: the structure of the instrument is wrong for the thing being sought. What's required is a different kind of attention.

You may notice this is not entirely unlike what someone has been telling you at the opening of each of these lectures.

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Let me put three things side by side.

Plotinus, third-century Alexandria, working from pure philosophical reasoning: at the root of everything is a single undivided principle, the One, from which all apparent multiplicity overflows without the source being diminished. The world of separate things is the outermost expression of something that is, at its ground, unified. The soul participates in that ground and can, through a particular kind of attention, recognise what it has never stopped being.

Boehme, 1600, a cobbler in Silesia, no Greek, almost certainly no Plotinus, working from what he described as a moment of direct vision in his workshop: before God, there is the Ungrund: the groundless ground. God must divide in order to know himself. The world of separate things is how undivided being becomes visible to itself. The division is not a mistake. It is the structure that makes self-knowledge possible.

Bohm, London, 1980, working from the mathematics of quantum mechanics and thirty years of thinking about what nonlocality implies: the separate objects of ordinary experience are the explicate order: the surface of a deeper implicate order in which the whole is present in each part. Separateness was never fundamental. The division is real at the surface and absent at the ground.

Three people who did not read each other (one of them couldn’t have, one almost certainly hadn’t) arriving at the same structural move. A deeper undivided ground. A world of apparent separation that is the surface expression of it. A path back, through a particular kind of attention, to what was never actually divided.

And then there is Federico Faggin, whom you met last time. A physicist and engineer, who argued from quantum mechanics and a night alone at Lake Tahoe that consciousness cannot emerge from unconscious matter, that it is already present at the most fundamental level of physical reality. That his father’s Plotinus and his own microprocessors were, in the end, asking the same question from opposite ends of the same corridor.

The costume changes. The architecture doesn’t.

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This is a footnote about a footnote.

After Feynman's death in 1988, Daniel F. Styer issued an emended edition of Quantum Mechanics and Path Integrals by Feynman and Hibbs (Dover, 2005/2010). Styer fixed hundreds of typographical, mathematical, and notational errors in the original while preserving Feynman’s text and style; the edition is endorsed by the Feynman family.

After a passage in which Feynman suggests that the probability interpretation of the wave function Ψ is likely “the only consistent interpretation of this quantity” (and gives reasons), Styer inserted this editorial footnote:

“Feynman’s hunch was wrong: in fact other consistent interpretations are possible. One such alternative is the de Broglie-Bohm formulation, described in David Bohm and B.J. Hiley, The Undivided Universe: an ontological interpretation of quantum theory (Routledge, London, 1993).”

It directly addresses Feynman’s claim (in the double-slit discussion and related remarks about the uniqueness of the probability interpretation / absence of any underlying “machinery”) by pointing to de Broglie-Bohm theory as a consistent alternative that supplies definite particle trajectories guided by the wave function. In that picture an electron goes through one particular slit while the pilot wave goes through both, producing the interference pattern via the guidance equation - exactly the mechanism Feynman said no one knew.

Ha! Victory!

10. CLOSING: FORWARD POINTER TO LECTURE 4

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I said at the opening of this evening that a small number of physicists, working from the equations of quantum mechanics, started arriving somewhere the esotericists would have found familiar. We've seen tonight that this is true, and that the parallel is not superficial: it is structural. Bohm's implicate order and Plotinus's One are not vaguely similar. They are the same move, made from opposite ends of intellectual history, meeting in the middle. And underneath the philosophy, tonight, you saw the mathematics that carries it: one field, real enough to hold up stars, dividing into many without ceasing to be one.

But Bohm's implicate order is still, technically, a theory about the physical universe. It says wholeness is fundamental, separateness is derived, the pilot wave field is a real entity pervading all of space. What it doesn't quite say, at least not in the physics, is anything direct about consciousness. About whether the mind observing the quantum system is not just entangled with what it observes but is, in some deeper sense, the same kind of thing.

That is where the next step goes.

In the 1990s, a mathematician who had spent his career on the geometry of spacetime and a physician who had spent his on the biology of anaesthesia began collaborating on a proposal that consciousness is not something brains produce but something the universe does, and that the specific mechanism involves quantum processes inside structures in neurons that, until their proposal, nobody had thought to look at.

The structures are called microtubules. The mathematician is Roger Penrose. He came to consciousness not from mystical intuition but from Gödel's incompleteness theorems, from a purely mathematical argument that certain features of human understanding cannot be reproduced by any computational algorithm, and that therefore something non-computational must be happening in the brain. The physician is Stuart Hameroff, and he came to it from a simple clinical observation: anaesthetics, substances with wildly different chemical structures and no obvious common mechanism, all reliably switch off consciousness. And they all, it turns out, target the same cellular structures.

The proposal is called Orchestrated Objective Reduction. It is controversial. It is also the point at which the conversation we have been building across three evenings (from Burton's embodied consciousness, through Plotinus's undescended soul, through Bohm's implicate order) becomes a conversation that some physicists and biologists are now having in print, with equations, about what consciousness actually is and where it actually lives.

And one more thing, because I owe it to you. Next time I will also put my own cards on the table. You have now seen, tonight, in the physics, that there is one universal field: real enough to hold up stars, undivided, guiding every particle there is. Next time I am going to suggest what that field might be. And I owe you an answer to tonight's homework question: what it would be like to be that field, before any partition. I warn you again: the answer will also turn out to be an answer to the question of what time is.

Next time. Bring your second mode of attention. We're going further in.