THE VALLICO ACADEMY LECTURE SERIES

LECTURE THREE

DE BROGLIE, BOHM, AND THE PILOT WAVE

Waves. Particles. Exile.

Quantum mechanics: the most successful theory in the history of physics, forbidden on principle from saying what is actually happening.

TWO WAYS OF PAYING ATTENTION

A reminder, and tonight's lens

THE FIRST MODE

Narrow · Analytical · Instrumental

Calculate the result of a measurement.
Don’t ask what is actually happening.

The recipe works.
Don’t open the box.

Copenhagen interpretation.
Dominant orthodoxy for
a hundred years.

→

THE SECOND MODE

Broad · Holistic · Realist

Demand an actual picture.
Ask what is really there.

Both the particle and
a pilot wave field exist.
Neither disappears when
you’re not looking.

De Broglie. Bohm.
The road not taken… until it was.

QUANTUM MECHANICS

THE PHYSICS OF THE VERY SMALL

Quantum mechanics describes the behavior of matter and energy at atomic and subatomic scales, where nature reveals its most fundamental and beautiful principles.

WAVE-PARTICLE DUALITY
Particles exhibit both particle-like and wave-like properties.

QUANTUM SUPERPOSITION
Systems exist in multiple states simultaneously until measured.

ENTANGLEMENT
Particles can be correlated in ways that defy classical separation.

UNCERTAINTY PRINCIPLE
Certain pairs of properties cannot be known with arbitrary precision.

$$i\hbar \frac{\partial \Psi}{\partial t} = \hat{H}\Psi$$

The equation that guides the quantum world.

"Not just how the universe is, but how it unfolds from possibility."

Atoms arranged with precision, revealing the quantum landscape beneath.

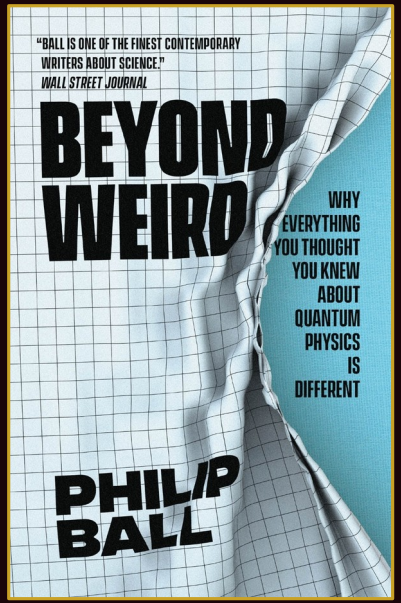
“It’s weirder than you can imagine.”

What the popular books tell you about quantum mechanics:

Observation brings reality into existence. Before you look, nothing is definite.

Particles are in two places at once. Cats are simultaneously alive and dead. This is a fact.

Nobody understands it. Not even the physicists. That’s just how it is.

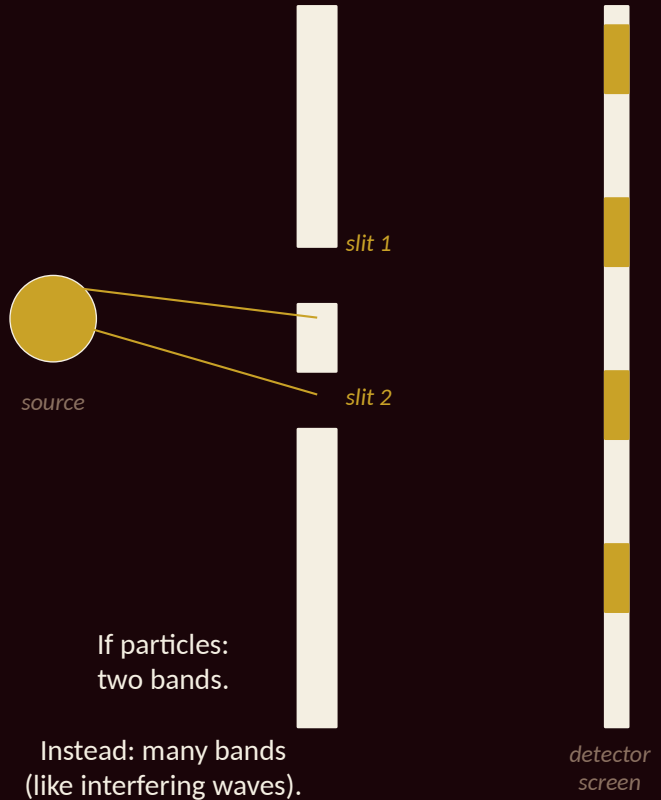


Philip Ball · *Beyond Weird*

How many of you have been told one or more of these things?

You’ve been sold a story. Let’s look at what’s actually going on.

THE ONLY MYSTERY



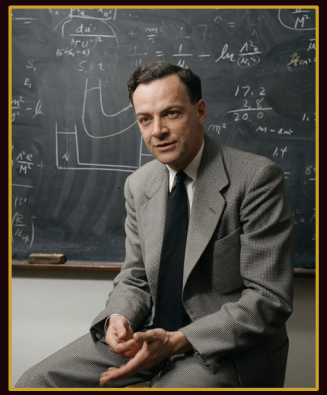
If particles:
two bands.

Instead: many bands
(like interfering waves).

RICHARD FEYNMAN

"The double-slit experiment has in it the heart of quantum mechanics."

"Nobody can explain why. Nobody knows. The mystery has never been explained."



(AI-restored photograph)

He was wrong.

The explanation existed. It had existed since 1927. He just didn't like it.

WHAT IS QUANTUM MECHANICS?

A precise answer, before we go any further:

Quantum mechanics is a probability calculus.

If you prepare a physical system in this way, these are the probabilities you will obtain for each possible measurement outcome. The theory produces these numbers with extraordinary, unmatched precision. It contains no story about what is actually happening between measurements.

That's it. That's the whole thing. It's an instruction manual for producing numbers.
And it works. No theory in the history of science has been more precisely confirmed.

The question is: what does this instruction manual describe? What is the reality it is about?
The Copenhagen answer: that question is meaningless. You've heard that move before.

THE MEASUREMENT PROBLEM

1

Before measurement:

The quantum system exists in a superposition: a sum of possible states, each with a probability amplitude. The electron is not at any definite position. It is everywhere it could be, weighted.

2

At measurement:

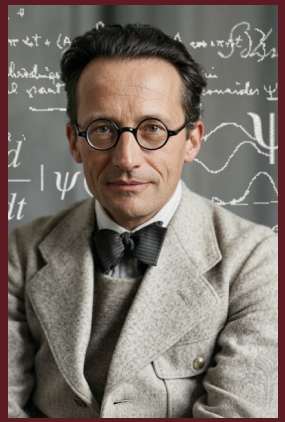
The superposition collapses. The electron is found at one definite location. The probability cloud becomes a single fact. Nobody knows how or why this happens.

3

The question nobody can answer:

What counts as a ‘measurement’? When does the quantum world end and the classical world begin? Is there a boundary? Where is it? Why?

This is the hinge of the whole debate. Copenhagen’s answer: don’t ask.



(AI-restored photograph)

ERWIN SCHRÖDINGER

1887–1961

Vienna
Graz · Zürich
Berlin · Dublin

Nobel Prize 1933
(shared with Dirac)

$$i\hbar \frac{\partial \Psi}{\partial t} = \left(-\frac{\hbar^2}{2m} \nabla^2 + V \right) \Psi$$

THE DARK LADY OF AROSA

December 1925. Schrödinger took a ski holiday at a villa in Arosa, Switzerland. He brought an old girlfriend whose name was never recorded: she appears in every biography as the ‘Dark Lady.’

He also brought the papers of a French physicist called Louis de Broglie, who had proposed that particles might have an associated wave.

Over the Christmas fortnight, in that villa, with that woman, working from those papers, Schrödinger produced the equation that bears his name. The wave equation of quantum mechanics, whose solution is the quantum-mechanical **wavefunction** Ψ.

The Nobel committee awarded him the prize in 1933, shared with Paul Dirac. His wife Anny reportedly negotiated, as part of the prize arrangements, that Schrödinger could bring both the woman he was currently with and the mother of his child. The teenage nymphette twins Ithi and Withi: his Nobel arrangement.

As I say. Another one Burton would have recognised.

Schrödinger's Cat, 2009

SCHRÖDINGER'S CAT

A sealed box. A cat.
A radioactive atom.
A vial of poison on a trigger.

The atom has a 50% chance of decaying in one hour.

Until you open the box…

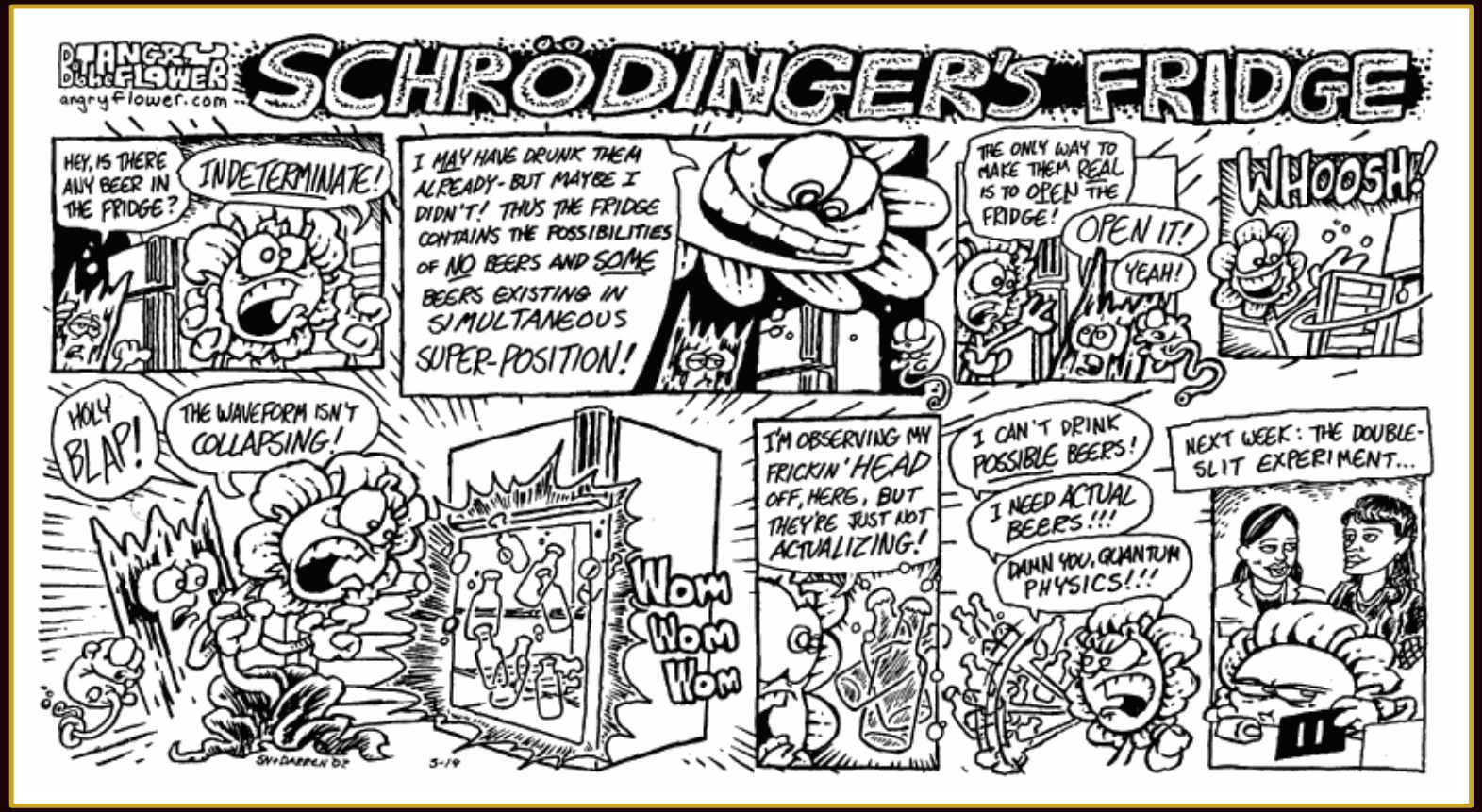
Copenhagen: the cat is simultaneously alive and dead.

Schrödinger's point: this is absurd.
He intended it as a reductio, not a triumph.

I, in 2009, at Cambridge, added a variant: 'Schrödinger's Woman.'

"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." (Cambridge University Physics Society, 21.10.2009)

SCHRÖDINGER'S FRIDGE



Bob the Angry Flower, by Stephen Notley (angryflower.com). As shown at Cambridge, 2009.

BRUSSELS

October 1927

The Fifth Solvay Conference. Find your character.

The Fifth Solvay International Conference on Physics. Invitation only. Twenty-nine people.

Seventeen had won or would win a Nobel Prize.

Einstein. Bohr. Curie. Heisenberg. Pauli. Born. Dirac. De Broglie.

Louis de Broglie, aged 35, stood up. He had a theory. Both the particle and the pilot wave field exist. The wave guides the particle. The double slit is not a mystery. It is explained.

He called it the pilot wave. What happened next changed everything.

I need six volunteers.

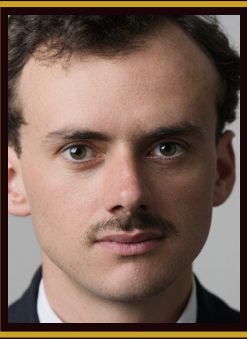
THE COPENHAGENISTS

NIELS BOHR · 1885–1962

The father figure. The interpretation is named after his address.

WERNER HEISENBERG · 1901–1976

Matrix mechanics. The uncertainty principle. Schrödinger's rival.



PAUL DIRAC · 1902–1984

The genius. The Dirac equation, antimatter. Rarely spoke.

WOLFGANG PAULI · 1900–1958

The attack dog. The exclusion principle. 'Not even wrong.'

(AI-restored photographs.)

THE SOLVAY PLAY: YOUR CAST

MR. DE BROGLIE

French. Highly intelligent. Masterful speaker.

You won.

MR. PAULI

Humourless Austrian. You are always right and you know it.

Ernst Stavro Blofeld.

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. You are about to threaten someone.

Ray Winstone.

MR. BRAGG

Posh English. Sits next to Heisenberg.

Unwise.

THE SOLVAY AUDIENCE

Everyone else.

Follow stage directions.

Exaggerate the accents. That's not optional.

UNIVERSE I

The One We Could Have Had

— DE BROGLIE presents the pilot wave. Enthusiastic applause.

— PAULI stands to congratulate him. His doubts, he finds, are resolved.

— BOHR proposes his alternative. The room is not kind.

— Men in white coats are involved. A different century of physics follows.

CURTAIN

UNIVERSE II

The One We Live In

- DE BROGLIE presents. The same words. Polite applause.
- PAULI objects: the rotator. Inelastic collisions. ‘As Fermi has shown…’
- DE BROGLIE replies. His answer holds the essential points. The room has moved on.
- Complementarity is installed. The pilot wave is set aside.
- Copenhagen wins. This is the universe we got.

Everything after this is different.

COPENHAGEN: WHAT IT ACTUALLY CLAIMS

1	The wavefunction is a complete description of physical reality. Nothing is hidden beneath it.
2	Physical quantities (position, momentum, spin) have no definite values before measurement. The question ‘where is it?’ has no answer until you look.
3	Measurement causes ‘collapse’: the indefinite becomes definite at the instant of observation.
4	There are no hidden variables beneath the wavefunction. No deeper structure. This is the bottom.
5	To ask what is ‘really happening’ between measurements is a meaningless question. Physics describes results, not reality.

Schrödinger called it ‘a philosophical extravaganza dictated by despair.’ He was not wrong.

THE CHORUS OF IMPOSSIBILITY

HEISENBERG, 1958:	*"The idea of an objective real world whose smallest parts exist objectively in the same sense as stones or trees exist, independently of whether or not we observe them... is impossible."*
WHEELER, 1983:	*"Every attempt, theoretical or observational, to defend such a hypothesis (the notion of hidden variables supplementing the wave function description) has been struck down."*
LANDAU & LIFSHITZ, 1977:	*"It is clear that [the double slit experiment] can in no way be reconciled with the idea that electrons move in paths. In quantum mechanics there is no such concept as the path of a particle."*
FEYNMAN, 1965:	*"How does it really work? What machinery is actually producing this thing? Nobody knows any machinery. Nobody can give you a deeper explanation of this phenomenon than I have given; that is, a description of it."*
OPPENHEIMER, 1953:	*"...We consider it juvenile deviationism... we don't waste our time... [by] actually read[ing] the paper. If we cannot disprove Bohm, then we must agree to ignore him."*
PRINCETON INSTITUTE, 1953:	*"[Bohm] is a public nuisance... a Trotskyite and a traitor."*
ROSENFELD:	*"[Bohm's work is] a short-lived decay product of the mechanistic philosophy of the nineteenth century."*

Every single one of them was wrong. An explanation existed. They chose not to use it.

Circular demonstrations of consistency, disguised as compelling arguments of inevitability.

(AI-restored photograph)

JOHN VON NEUMANN

1903–1957

Budapest
Princeton
Manhattan Project

Mathematical Foundations of Quantum Mechanics
1932

One of the most influential wrong proofs in the history of science.

THE PROOF THAT WASN'T

In 1932, John von Neumann (one of the greatest mathematicians of the century) published a book purporting to prove, rigorously, that no hidden-variable theory could reproduce the predictions of quantum mechanics.

In other words: pilot wave theories are mathematically impossible. Full stop.

Physicists cited this proof for decades. Heisenberg cited it. Dirac cited it. It became one of the primary reasons physicists felt they could stop looking for an alternative to Copenhagen.

The proof was circular. Von Neumann had smuggled his conclusion into his assumptions. If you assumed that hidden variables must satisfy certain constraints (the same constraints as quantum observables) of course they came out impossible. The constraints were arbitrary.

Nobody noticed for three decades. Or if they noticed, they didn't say so.

(AI-restored photograph)

GRETE HERMANN

1901–1984

Bremen
Leipzig
Göttingen

Philosopher. Mathematician.
Student of Emmy Noether.

Found the flaw.
Not a physicist.
Not heard.

THE THIRD TIME

In 1935 (three years after von Neumann published his proof) Grete Hermann, a German philosopher and mathematician working at Göttingen, published a detailed paper identifying the exact flaw in the proof.

She was right. The argument was airtight. Von Neumann's proof assumed what it was trying to prove.

The paper was published in a philosophy journal. Physicists did not read it. It had essentially no impact on the development of quantum mechanics.

The flaw was rediscovered independently by John Bell in 1966. Bell published in a physics journal. This time, people listened.

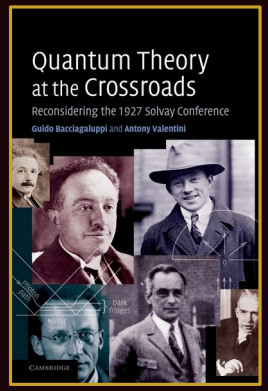
Thirty-one years.

The Gnostics had it for longer. Boehme had it for longer. But the pattern is the same.

THE PIVOT

> ***"In 1952 I saw the impossible done. It was done by David Bohm."***
>
> *John Stewart Bell, CERN physicist, author of Bell's Theorem*
> *Interview with Paul Davies, 1985*
>
> *Read this sentence again. Let it land.*

David Bohm (AI-restored photograph)

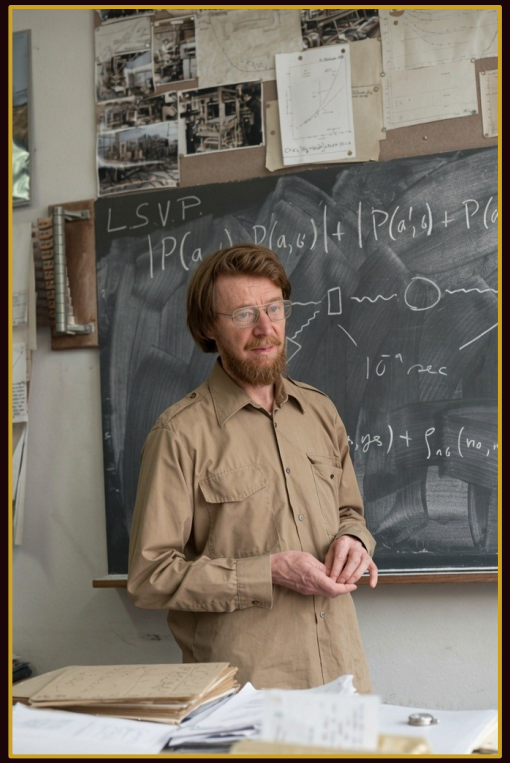


In the Academy Library.

And to give credit where it's due, what Bohm had done was essentially the same as de Broglie's theory of 1927, with a more careful treatment of the measurement problem. Which is why today, we call this de Broglie-Bohm theory.

Believe it or not, what de Broglie had achieved was only made completely clear when a dusty copy of the Solvay 1927 proceedings was translated from French into English for the first time.

Bacciagaluppi & Valentini, *Quantum Theory at the Crossroads: Reconsidering the 1927 Solvay Conference* (2009).



(AI-restored photograph)

> ***“Copenhagen is so deeply ingrained in most physicists that they cannot imagine any alternative. The only way for the situation to improve is for most of them to die, so that the next generation can grow up without the prejudice.”***

John Stewart Bell · CERN · c. 1985

He said this out loud. To a journalist. While working at CERN.
This is a description of a sociology, not a science.

CHANGE ONE WORD

The entire difference between the two interpretations

WHAT YOU WERE TAUGHT

$|\Psi|^2$ is the probability of **FINDING** the electron at x, in a suitable measurement.

The particle has no position until you look.

→

WHAT DE BROGLIE SAID

$|\Psi|^2$ is the probability of the electron **BEING** at x.

The particle is always somewhere.
You just don't know where.

That is the entire difference. Particles exist whether or not you look. A theory of measurement becomes a theory of motion: Newton's laws, with one extra force.

Newton's equations of classical mechanics can be rewritten as:

$$i\hbar\,\partial\Psi/\partial t = \left(-\hbar^2/2m\,\nabla^2 + V - Q\right)\Psi$$

the time-dependent Schrödinger equation, with an extra −Q term.

So quantum mechanics is just like classical statistical mechanics with a non-classical dynamics.

PILOT WAVE THEORY

THE PARTICLE

Always in a definite position.
Always moving along
a definite trajectory.
Goes through one slit.
Only one.

guides

←

THE PILOT WAVE FIELD

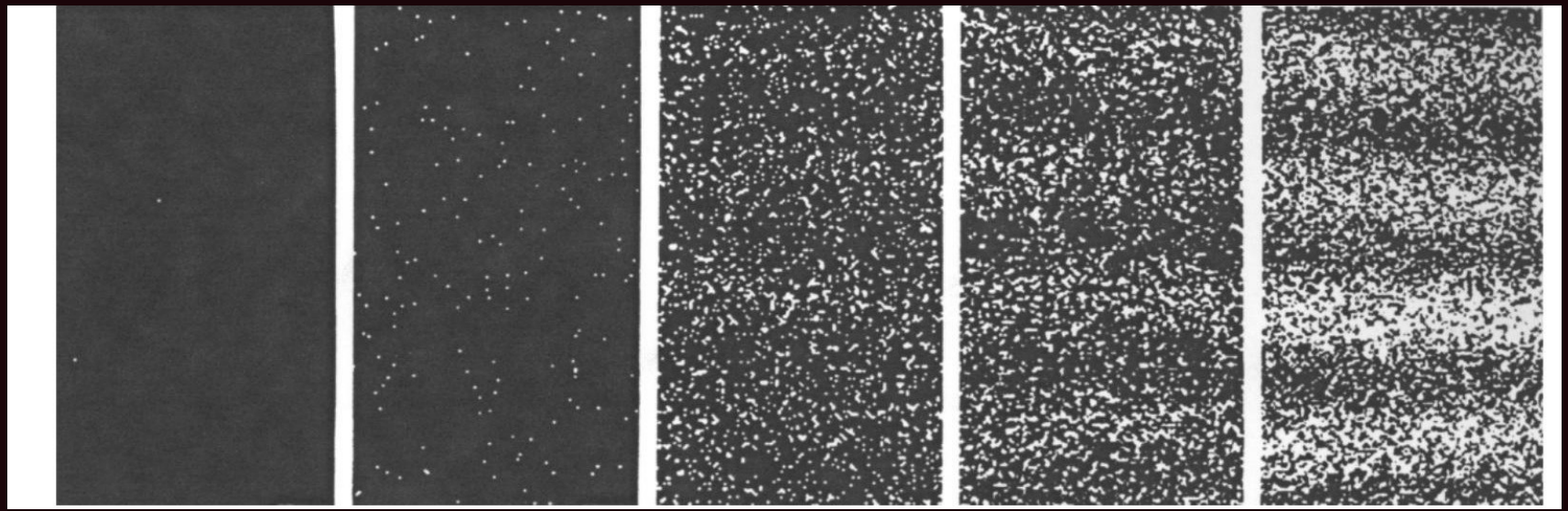
Exists everywhere the particle could be.

Passes through both slits.

Its structure determines where the particle is likely to go, because the extra force depends on the *curvature* of the pilot wave field at any point.

The second mode of attention, applied to physics: both things exist. Neither is sacrificed for mathematical convenience.

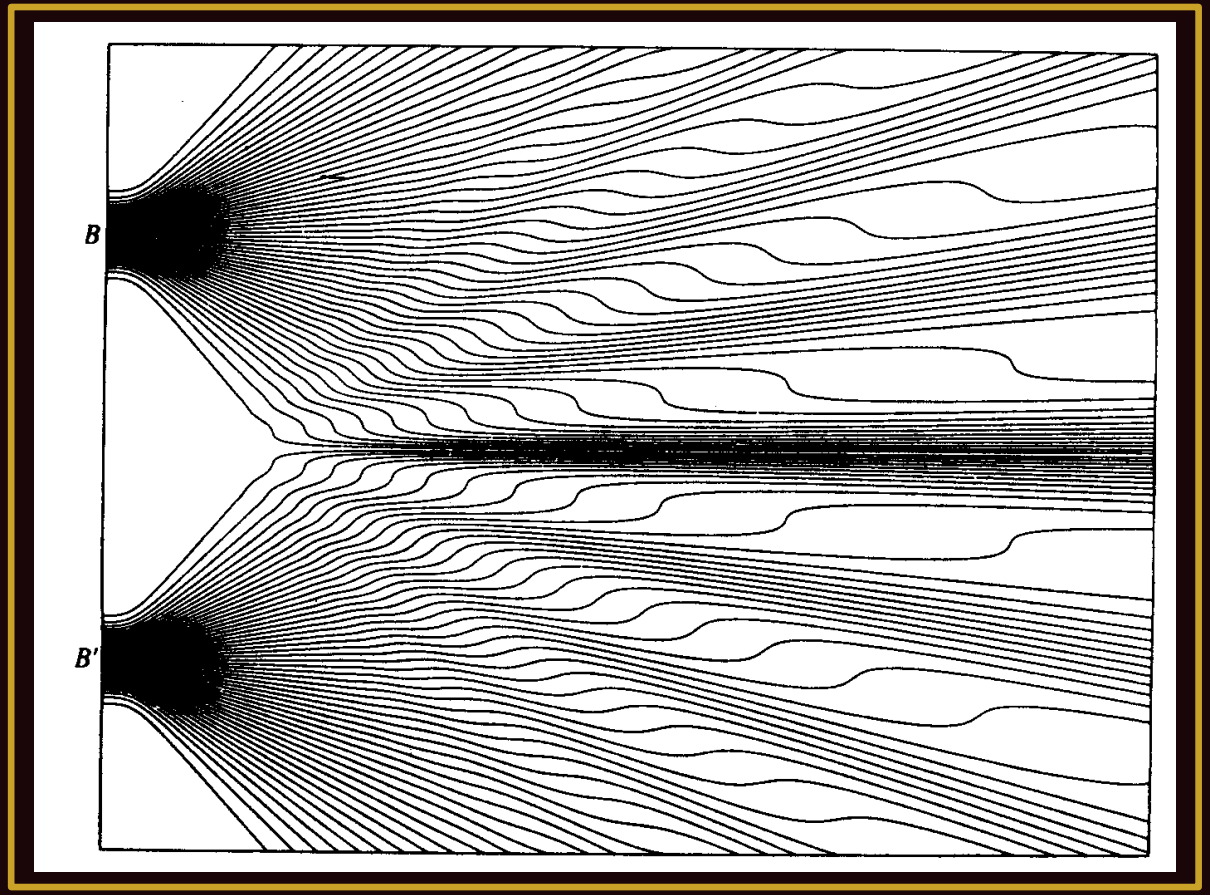
ONE ELECTRON AT A TIME



◄ *fewer electrons*

more electrons ►

Each electron hits as a single dot. No pattern at first. Add enough electrons, and the interference fringes emerge.



Calculated particle paths in a pilot-wave universe. B and B' are the two slits.
Each line is one particle. None of them are in two places at once.
Philippidis, Dewdney & Hiley (1979)

WHAT HOLDS UP A DYING STAR?

A white dwarf: a star out of fuel, collapsing under its own gravity, and then stopping. Something is holding it up.

The four 'fundamental forces of nature':

~~GRAVITY~~ ***(this one is trying to kill it)***

~~ELECTROMAGNETISM~~

~~WEAK NUCLEAR FORCE~~

~~STRONG NUCLEAR FORCE~~

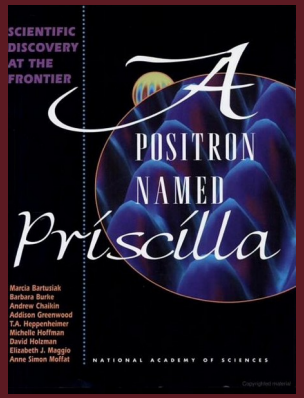
None of them is responsible.

What stops the collapse is 'electron degeneracy pressure': a force strong enough to hold up a star. It is the quantum force: the push of the pilot wave field.

PRISCILLA

a positron

Hans Dehmelt
University of Washington
Nobel Prize 1989



ONE PARTICLE. KNOWN INDIVIDUALLY.

Hans Dehmelt, at the University of Washington, held a single positron in a magnetic trap for three months. He measured its magnetic moment to twelve decimal places.

He named her Priscilla.

Not a collection of electrons averaged over statistical experiments. One particle. Known individually. Trapped, measured, studied.

For this technique, Dehmelt shared the Nobel Prize in Physics in 1989.

Why does this matter? Because the Copenhagen argument for why quantum mechanics must be statistical (why you cannot ask where one particle is) was partly motivated by the assumption that individual quantum systems are too small and too brief to study directly.

Priscilla dissolves that assumption.

ASTRID

a barium atom

Ba^+
Trapped and illuminated
under UV light

visible to the naked eye · 10 months

Smallness is
not the issue.

SEEN WITH THE NAKED EYE

A barium ion, trapped in a Paul trap and illuminated under ultraviolet light, fluoresces. If the trap is clean and the ion is bright, you can see it with the naked eye: a tiny blue-white point of light, hanging in space.

Astrid was kept for ten months. She was not a statistical average over a million experiments. She was one ion, studied over time.

The argument 'quantum systems are too small to track as individuals' is not wrong in practice. It is wrong in principle.

The Copenhagen claim (that there is no fact of the matter about where the particle is) is a philosophical position. It is not forced on us by the impossibility of isolating individual quantum systems.

Smallness is not the issue. The issue is the interpretation.

(AI-restored photograph)

JOHN STEWART BELL

1928–1990

CERN physicist
Belfast

Bell's Theorem
1964

The universe is nonlocally connected. This is not a metaphor.

THE THEOREM

Einstein, Podolsky and Rosen, 1935: if quantum mechanics is correct, then measuring one particle of an entangled pair must instantly affect the result of measuring the other, no matter how far apart they are. This is absurd, said Einstein. Therefore quantum mechanics is incomplete.

Bell, 1964: you can test this. If quantum mechanics is just our ignorance of hidden variables that travel locally, the correlations between entangled pairs must satisfy certain inequalities. Bell derived the inequality.

Aspect, 1982: the inequality is violated. The correlations are stronger than any local hidden variable theory can produce.

Conclusion: the universe is nonlocally connected. Measuring one particle really does affect another, instantaneously, regardless of distance.

Note: pilot wave theory requires nonlocality. Bohm knew this. He considered it a feature, not a flaw.

(AI-enhanced photograph)

DAVID BOHM

1917–1992

Pennsylvania
Princeton
Brazil · Israel
Birkbeck, London

Student of Oppenheimer.
McCarthy-era exile.

The man who kept asking.

THE EXILE

David Bohm was Robert Oppenheimer's student at Berkeley. Brilliant. One of the clearest expositors of quantum mechanics in the world: his textbook on the subject is still in print.

In 1949, he was subpoenaed by the House Un-American Activities Committee. He refused to name names. Oppenheimer, when asked to provide a character reference that might have cleared him, declined. Princeton declined to renew his contract.

His Princeton colleagues called him a public nuisance, a Trotskyite, a traitor. He was forced to leave the United States.

He went to Brazil. Then Israel. Eventually London, where Birkbeck College gave him a post.

In 1951, under subpoena at Princeton, he wrote the two papers on the pilot wave; they appeared in 1952, just as he reached Brazil. Bell called it the impossible done.

He went on asking. He never stopped.

VALLICO SOTTO

August 2010

21st-Century Directions in
de Broglie-Bohm Theory and Beyond.

The biggest conference this building has ever hosted. I organised it with Antony Valentini.

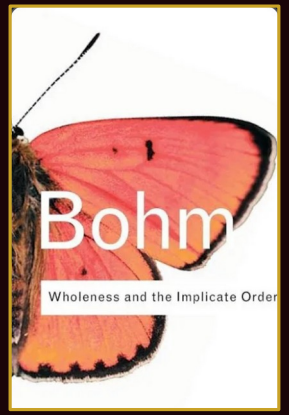
Basil Hiley is in this photograph. Bohm's closest collaborator. Co-author of The Undivided Universe. Died 2025. Sixty years keeping the flame alive.

Sam is in the photograph. Saska was five years old and very much present. She is not in the photograph. I'll leave that to her to explain.

Out of this conference came a paper: Towler, Russell and Valentini, Proc. Roy. Soc. A 468, 990–1013 (2012). My only deBB publication. Still there.

THE IMPLICATE ORDER

> *"The order of the universe is not the order of separately existing things. It is an implicate order — an undivided wholeness in flowing movement, in which each part enfolds and is enfolded by the whole."*



David Bohm, Wholeness and the Implicate Order, 1980

Bohm distinguished between the ***explicate order*** (the world of distinct, separate things we interact with daily) and the ***implicate order*** (an undivided wholeness in which all things are enfolded into each other).

The pilot wave is the first sign of the implicate order in physics: a global field, nonseparable, that enfolds all particles and guides each one according to the whole.

The implicate order is to the explicate order what Plotinus's One is to the world of matter. Bohm read the equations. He didn't need Plotinus.

ONE FIELD

Strictly speaking, there is one wave function: for the universe. Every particle in this room, in you, in the farthest galaxy, is guided by the same undivided object.

$$\Psi(\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_N)$$

where N is the number of particles in the universe

What makes anything separate (an atom, an instrument, a person) is a partition: the one field factorising into pieces that no longer touch each other.

The pieces are many. The field is one.

One thing becoming many without ceasing to be one.
You have heard that architecture before.

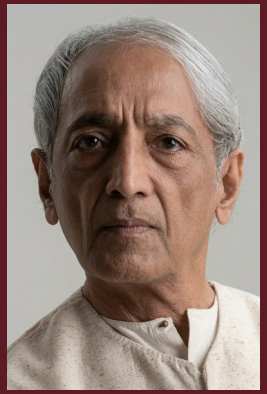
BOHM & KRISHNAMURTI

(AI-restored photograph)

DAVID BOHM

Physicist.
Implicate order.
Consciousness
as a physical process
of movement and
folding.

←— 30 years of dialogue —→



(AI-restored photograph)

JIDDU KRISHNAMURTI

Philosopher.
The dissolution
of the observer.
Thought cannot
resolve what
thought created.

The Theosophical Society brought Krishnamurti to the West. It is the same tradition we traced last time. The connections are not accidental.

THREE ROADS, ONE ARCHITECTURE

PLOTINUS

Third century, Alexandria

The One overflows into Nous and Soul and Matter. The world of separate things is the outermost ring of a prior unity. Epistrophe: the soul's return to that unity through contemplation.

BOEHME

17th century, Silesia

The Ungrund must self-divide to know itself. Matter is how the divine becomes visible to itself. Darkness and light are not opposites; darkness is the necessary precondition of self-knowledge.

BOHM

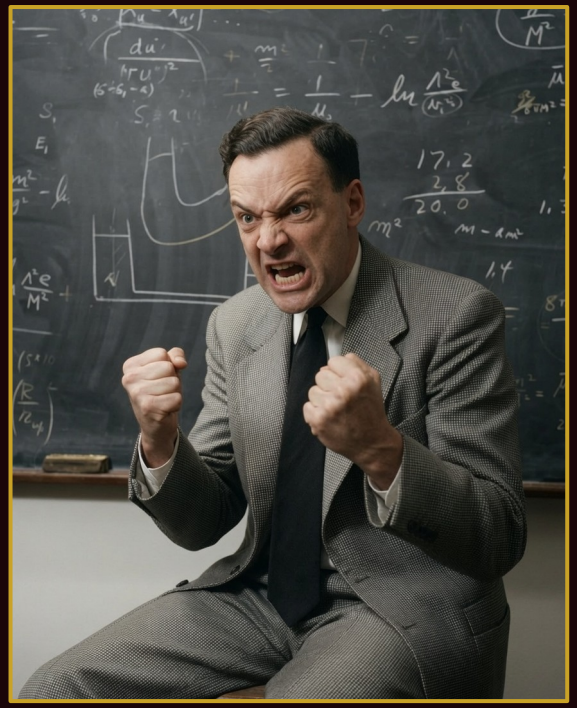
20th century, quantum mechanics

The explicate order of separate things unfolds from an implicate order of undivided wholeness. The pilot wave field is the first sign of the implicate. Consciousness and matter may both be stable patterns of movement in the implicate order.

RECALL: Federico Faggin (Lecture 2)

The inventor of the microprocessor, having a non-negotiable experience of consciousness during a meditation in 1990, concluding that unconscious matter cannot produce consciousness. His father's Italian translation of the Enneads of Plotinus. The chain from the Alexandrian rooms to the Intel boardroom is shorter than it looks.

The costume changes. The architecture doesn't.



TRIUMPHALIST FOOTNOTE

Feynman and Hibbs, Quantum Mechanics and Path Integrals. Daniel F. Styer's emended edition (Dover) repaired hundreds of slips in the original and carries the family's blessing.

> “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).”

Daniel F. Styer, editorial footnote, emended edition

Ha! Victory!

NEXT TIME

CONSCIOUSNESS IN THE EQUATIONS

Roger Penrose · Stuart Hameroff · Orchestrated Objective Reduction

Microtubules. Quantum coherence in the brain. The hard problem of consciousness.
And a suggestion for what the field might be.

Tonight we showed that the second mode of attention (the demand for a real picture, the refusal to declare questions out of order) produces better physics than the first.

Next time: what happens when that same second mode is applied to the question of consciousness itself.

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