The Double-Slit Experiment

How Nature Led Us from Classical Intuition to Quantum Mechanics

Big Idea

The double-slit experiment asks a very simple question:

What happens when a quantum object has two possible paths?

The answer is surprising. An electron is detected at one specific location, yet many electron detections can form an interference pattern similar to a wave.
This experiment gives us a concrete way to understand **probability amplitudes, interference, superposition, and measurement**.

1 What Should You Be Able to Explain?

By the end of this lecture, you should be able to:

1. predict what ordinary particles should do in a two-slit experiment;
2. explain why ordinary waves produce an interference pattern;
3. describe what happens when electrons are sent through the apparatus one at a time;
4. explain the difference between adding probabilities and adding probability amplitudes;
5. explain what changes when we measure which path an electron takes;
6. connect the double-slit experiment to superposition and a qubit.

The goal is not to memorize equations first. We will first understand **what happens physically**, and then introduce the mathematics that describes it.

2 How Did We Get Here?

The double-slit experiment is part of a much longer scientific story.

Period	**Scientists**	**Main idea or result**
5th century BCE	Leucippus and Democritus	Proposed that matter could be understood as extremely small pieces, or atoms, moving through empty space [1].
1801–1804	Thomas Young	Developed and experimentally supported the principle of interference of light, helping establish the wave description of light [2, 3].
1924	Louis de Broglie	Proposed that matter such as electrons could also exhibit wave-like behavior [4].
1926	Erwin Schrödinger and Max Born	Schrödinger developed wave mechanics. Born connected the wavefunction to measurement probabilities [5, 6].
1927	Clinton Davisson, Lester Germer, and George Paget Thomson	Experiments demonstrated electron diffraction, providing direct evidence of wave-like behavior of electrons [7, 8].
1961	Claus Jönsson	Demonstrated electron interference using fabricated slits in an arrangement analogous to Young's optical experiment [9].
1965	Richard Feynman, Robert Leighton, and Matthew Sands	Presented the now-famous particles–waves–electrons comparison as a way to introduce the central ideas of quantum mechanics [10].
1976–1989	P. G. Merli, G. F. Missiroli, G. Pozzi; Akira Tonomura and colleagues	Recorded individual electron detections while an interference pattern gradually emerged [11, 12].
2013	Roger Bach, Damian Pope, Sy-Hwang Liou, and Herman Batelaan	Performed a controlled realization of the double-slit experiment with individual electrons [13].

We will now reconstruct this story experimentally.

3 Start with Everyday Intuition

More than two thousand years ago, **Leucippus and Democritus** suggested that the physical world could be understood using tiny indivisible pieces moving through empty space [1].

The Greek word *atomos* means roughly "uncuttable" or "indivisible."

Their atoms were not the atoms of modern physics. We now know that atoms contain electrons and nuclei and can themselves be divided into smaller constituents.

The important lesson is different. They were trying to answer a question that scientists still ask:

What is nature made of, and how do those pieces behave?

Think about a baseball.

At a given time, we normally imagine that the baseball:

- is at one location;
- follows one path;
- does not travel through two separate openings at the same time.

This is a useful example of **classical particle intuition**.

Our everyday intuition is built from large objects such as baseballs, cars, and grains of sand.
There is no guarantee that an electron must behave like a very small baseball.

How do we determine which picture is correct?
We perform an experiment.

4 The Basic Experiment

The apparatus contains only three important pieces:

Source ⟶ Two Slits ⟶ Detection Screen.

The source sends something toward a barrier containing two narrow openings.
We call the openings

$$S_1 \quad \text{and} \quad S_2.$$

Behind the barrier is a screen that records where something arrives.

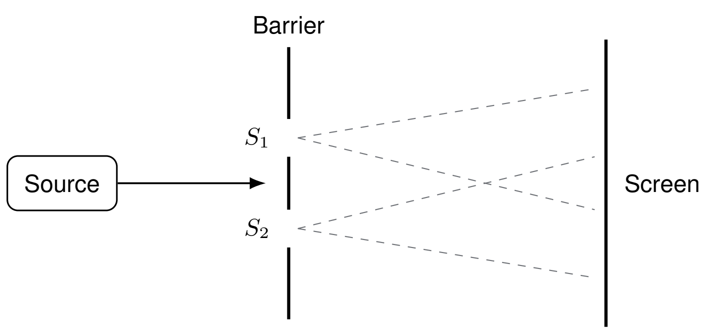

Figure 1: A conceptual two-slit experiment.

We will run this experiment three times:

1. with ordinary particles,
2. with ordinary waves,
3. with electrons.

The important rule for today's class is:

Predict first. Observe second. Explain third.

5 Experiment 1 – Ordinary Particles

Imagine that the source fires tiny solid balls.
Each ball eventually produces one hit on the screen.
First close slit S_2 and leave only S_1 open.
After sending many balls, we obtain a distribution of hits. We will call it

$$P_1(x).$$

Here, x simply means a location on the detection screen.

Now close slit S_1 and open only S_2. We obtain a second distribution:

$$P_2(x).$$

Pause and Predict

Now open **both** slits.
What should happen if the balls behave like ordinary classical particles?
Should opening the second slit somehow create locations where *fewer* balls arrive?

No.

A ball passing through slit 1 contributes to the first distribution. A ball passing through slit 2 contributes to the second distribution.

The two groups simply add.

For our idealized classical-particle experiment,

$$\boxed{P_{12}(x) = P_1(x) + P_2(x).}$$

In plain English:

$$\boxed{\text{hits through } S_1 + \text{hits through } S_2 = \text{total hits.}}$$

For example, suppose that near one small region of the screen:

$$30$$

balls arrive when only slit 1 is open, and

$$20$$

arrive when only slit 2 is open.

With both slits available, our classical expectation is approximately

$$30 + 20 = 50.$$

Big Idea

For ordinary classical particles, the alternatives behave like separate groups of events.

$$\boxed{\text{The probabilities add.}}$$

6 Experiment 2 – Ordinary Waves

Now replace the balls with water waves.

A wave reaches the barrier and passes through both openings.

Each opening produces an outgoing wave. The two outgoing waves then overlap.

What happens when waves overlap?

Case 1 – Peak Meets Peak

Suppose the high part of one wave meets the high part of another.
They reinforce each other:

$$\text{peak} + \text{peak} \quad \longrightarrow \quad \text{larger wave.}$$

This is called

$$\boxed{\textbf{constructive interference}}.$$

Case 2 – Peak Meets Trough

Now suppose the high part of one wave meets the low part of another.
They can partially or completely cancel:

$$\text{peak} + \text{trough} \quad \longrightarrow \quad \text{smaller wave.}$$

This is called

$$\boxed{\textbf{destructive interference}}.$$

Big Idea

Waves can do something that our classical balls could not do:

$$\boxed{\text{two contributions can reinforce or cancel.}}$$

This produces alternating regions of stronger and weaker wave intensity.
That pattern is called an

$$\boxed{\textbf{interference pattern}}.$$

7 A Simple Way to Understand Wave Interference

We can represent a wave at one location using an **amplitude**.
For example, imagine that one wave contributes

$$A_1 = +1$$

and another contributes

$$A_2 = +1.$$

They reinforce:

$$A_{\text{total}} = A_1 + A_2 = 1 + 1 = 2.$$

Now suppose instead that

$$A_1 = +1, \qquad A_2 = -1.$$

The positive and negative signs represent opposite parts of the wave, such as a peak and a trough. Then

$$A_{\text{total}} = 1 - 1 = 0.$$

The waves cancel.

> The important idea is not the numbers $+1$ and -1.
> The important idea is the order:
>
> combine the wave amplitudes first $\longrightarrow$ then determine the intensity.

At some locations, the waves arrive “in step” and reinforce.

At other locations, they arrive “out of step” and cancel.

Later, we will call this relative position in the wave cycle **phase**.

For now, simply remember:

same timing $\rightarrow$ reinforcement

and

opposite timing $\rightarrow$ cancellation.

8 Particles and Waves Behave Differently

We have now established two very different expectations.

System	**What combines?**	**What should we see?**
Ordinary particles	Probabilities	Two particle distributions that simply add
Ordinary waves	Wave amplitudes	Reinforcement and cancellation, producing interference

This gives us an experimental test.

If electrons behave exactly like tiny classical balls, we should get the first pattern.

If electrons show wave-like interference, we should get the second.

9 Why Would Anyone Expect an Electron to Behave Like a Wave?

For a long time, electrons were naturally imagined as particles.

Then, in 1924, French physicist **Louis de Broglie** proposed a remarkable idea.

Light was known to show wave behavior, yet quantum experiments had also revealed particle-like behavior.

De Broglie asked:

**If something we call a wave can behave like a particle,
could something we call a particle also behave like a wave?**

He proposed that matter, including electrons, has an associated wavelength [4].

This idea made experimental predictions.

In 1927, **Clinton Davisson and Lester Germer** observed diffraction when electrons scattered from a nickel crystal [7].

At about the same time, **George Paget Thomson** independently observed electron diffraction using thin films. Davisson and Thomson later shared the 1937 Nobel Prize in Physics for the experimental discovery of electron diffraction by crystals [8].

Historical Connection

Notice how science progressed:

de Broglie made a prediction $\longrightarrow$ experiments tested it.

The result was not simply a philosophical statement that matter is “kind of wave-like.” Electron diffraction was something that could actually be measured.

Now we are ready for the two-slit electron experiment.

10 Experiment 3 – Electrons

Replace the balls and water waves with electrons.

Pause and Predict

Suppose an electron is simply a tiny classical particle.
What should we expect when both slits are open?

$$P_{12}(x) = P_1(x) + P_2(x)$$

or

an interference pattern?

Make a prediction before continuing.

If electrons behaved exactly like tiny classical balls, the natural prediction would be

$$P_{12}(x) = P_1(x) + P_2(x).$$

But experiments do not give that result.

Instead, electrons produce interference.

11 First Surprise – Each Electron Arrives at One Place

Make the electron source weak enough that individual electron detections can be separated in time.

One electron reaches the screen.

It is detected at one location:

Later, another electron arrives at another location:

Each detection is localized.

The electron is not detected as half an electron in one place and half an electron somewhere else.

At the detector:

$$\boxed{\text{one electron} \longrightarrow \text{one localized detection.}}$$

That looks particle-like.

12 Second Surprise – Keep Sending Electrons

Now repeat the experiment.

After only a few electrons, the locations may appear scattered and almost random.

After many more electrons, something begins to appear.

Some locations receive many detections.

Other locations receive very few.

Eventually, the individual dots form an **interference pattern**.

Big Idea

This is the central surprise:

each electron arrives as one localized detection,
but many detections build a wave-like interference pattern.

The experiment can be performed at sufficiently low intensity that individual electron arrivals are clearly separated.

Therefore, the pattern cannot simply be explained by electrons colliding with one another on their way through the apparatus.

13 Was This Actually Done?

Yes.

Claus Jönsson demonstrated electron interference using fabricated slits in 1961 [9].

In 1976, **Pier Giorgio Merli, Gian Franco Missiroli, and Giulio Pozzi** reported an experiment emphasizing the statistical buildup of electron interference [11].

In 1989, **Akira Tonomura, J. Endo, T. Matsuda, T. Kawasaki, and H. Ezawa** published the famous demonstration in which individual electron detections gradually formed an interference pattern [12].

The Tonomura experiment used an **electron biprism**. An electron biprism is a device that creates two electron paths and brings them back together so they can interfere. It plays a role similar to the two slits, although it is not literally a wall containing two openings.

In 2013, **Roger Bach, Damian Pope, Sy-Hwang Liou, and Herman Batelaan** demonstrated a controlled version using a physical double-slit arrangement and individual electrons [13].

Historical Connection

The famous "dots slowly becoming interference fringes" picture is therefore not merely an illustration invented for a textbook.
It represents experimentally observed quantum behavior.

14 So Is an Electron a Particle or a Wave?

A common statement is:

"An electron is both a particle and a wave."

This is easy to remember, but it can also be misleading.

It may make us imagine that an electron is literally a tiny ball that sometimes transforms into a water wave.

That is not the right picture.

A more useful statement is:

Big Idea

An electron is a **quantum object**.
It produces localized detection events, while the probabilities of those events can display interference.

The words "particle" and "wave" describe familiar classical objects.

An electron follows quantum rules that do not fit perfectly into either classical category.

15 What Is Actually Interfering?

This is the most important conceptual question in the lecture.

If each electron arrives as one localized event, what produces the interference pattern?

Quantum mechanics introduces a quantity called a

$$\boxed{\textbf{probability amplitude}}.$$

Do not make this term more complicated than it needs to be.

For now:

A probability amplitude is a quantity we combine before calculating a probability.

Let

$$\psi_1(x)$$

represent the probability amplitude associated with reaching a small region near position x through slit 1.

Let

$$\psi_2(x)$$

represent the amplitude associated with reaching that region through slit 2.

The symbol ψ, pronounced "psi," is commonly used for a quantum wavefunction.

16 Schrödinger and Born

In 1926, **Erwin Schrödinger** developed wave mechanics and the equation now called the **Schrödinger equation** [5].

The equation tells us how the quantum state changes with time.

But an important question remained:

What does the wavefunction ψ tell us about an experiment?

Max Born supplied the crucial probabilistic interpretation.

The rule we need today is

$$\boxed{P(x) = |\psi(x)|^2.}$$

More precisely, $|\psi(x)|^2$ describes how likely a detection is near position x.[1]

Born later received part of the 1954 Nobel Prize in Physics, specifically recognizing his statistical interpretation of the wavefunction [6].

Do not confuse these two quantities:

$$\boxed{\psi = \text{probability amplitude}}$$

while

$$\boxed{|\psi|^2 = \text{measurement probability information.}}$$

An amplitude is **not** itself a probability.

17 One Slit at a Time

If only slit 1 is available, the probability pattern is determined by

$$P_1(x) = |\psi_1(x)|^2.$$

If only slit 2 is available,

$$P_2(x) = |\psi_2(x)|^2.$$

So far, this may look similar to ordinary probability.

The surprise comes when both paths are available.

[1] In a more advanced treatment, $|\psi(x)|^2$ is called a probability density.

18 Both Slits Open – The Quantum Rule

When both alternatives are available and the experiment does not create a record identifying which path occurred, quantum mechanics tells us to combine the **amplitudes first**:

$$\boxed{\psi_{12}(x) = \psi_1(x) + \psi_2(x).}$$

Only then do we calculate the probability pattern:

$$\boxed{P_{12}(x) = |\psi_1(x) + \psi_2(x)|^2.}$$

This is generally **not** equal to

$$P_1(x) + P_2(x).$$

Therefore,

$$\boxed{P_{12}(x) \neq P_1(x) + P_2(x)}$$

in general.
That difference is what produces quantum interference.

19 Make the Equation Concrete

Let us use deliberately simple numbers.
These numbers are only a teaching example. They are not measurements from a particular experiment.
Suppose that at one location:

$$\psi_1 = 0.3 \qquad \text{and} \qquad \psi_2 = 0.3.$$

First combine the amplitudes:

$$\psi_{\text{total}} = 0.3 + 0.3 = 0.6.$$

Now square the magnitude:

$$P = |0.6|^2 = 0.36.$$

The amplitudes reinforced.
Now consider another location:

$$\psi_1 = 0.3, \qquad \psi_2 = -0.3.$$

Combine them first:

$$\psi_{\text{total}} = 0.3 - 0.3 = 0.$$

Then

$$P = |0|^2 = 0.$$

The amplitudes canceled.

Big Idea

The quantum rule is:

Add amplitudes first. Then calculate probabilities.

Because amplitudes can reinforce or cancel, the final probability pattern contains interference.

Notice something important:

$$\psi = -0.3$$

does **not** mean "negative probability."

Its probability contribution by itself would be

$$|-0.3|^2 = 0.09.$$

The sign affects how amplitudes combine.

Later, we will learn that quantum amplitudes are generally **complex numbers**. We do not need complex-number mathematics to understand today's central idea.

20 Compare the Three Experiments

System	**What combines?**	**Result**
Classical particles	Probabilities	Two particle distributions simply add
Classical waves	Wave amplitudes	Constructive and destructive interference
Electrons with no path record	Quantum probability amplitudes	Individual detections build an interference pattern

This comparison is the heart of the experiment.

21 The Question Everyone Asks

At this point, a very natural question appears:

Which slit did the electron actually pass through?

Perhaps we can simply check.

Place a detector near the openings.

If the detector identifies slit 1, record:

$$\boxed{S_1}.$$

If it identifies slit 2, record:

$$\boxed{S_2}.$$

Then repeat the experiment.

22 What Happens When We Measure the Path?

Suppose our detector can perfectly determine which path was taken.
Now each electron leaves a physical path record:

$$\text{electron detected through } S_1$$

or

$$\text{electron detected through } S_2.$$

When the path is determined perfectly, the original two-path interference pattern disappears.
Instead, the result becomes the particle-like combination:

$$\boxed{P_{\text{path measured}}(x) = P_1(x) + P_2(x).}$$

This is one of the most important results in quantum mechanics.

23 What Does "Observation" Really Mean?

People sometimes describe the result by saying:

"The electron behaves differently when someone watches it."

That wording is memorable, but it creates a serious misconception.

Big Idea

A human being does **not** have to look at the experiment.
In quantum mechanics, measurement involves a **physical interaction that produces information about the system**.

Imagine that a detector automatically stores the result:

```
electron 37:  slit 1
```

in a computer file.
Nobody opens the file.
Nobody even enters the laboratory.
The physical path measurement has still occurred.
The important change is not human awareness.
The important change is that the experiment has created a physical record that distinguishes the two paths.

24 A Concrete Way to Think About Path Information

Imagine giving each path a perfectly readable tag.

$$S_1 \longrightarrow \boxed{\text{tag 1}}$$

$$S_2 \longrightarrow \boxed{\text{tag 2}}.$$

Before the tagging, nothing in the experiment tells us which alternative occurred.
After perfect tagging, the two alternatives can be told apart.
For the ideal experiment:

$$\boxed{\text{no path information} \longrightarrow \text{interference}}$$

while

$$\boxed{\text{perfect path information} \longrightarrow \text{no two-path interference.}}$$

> Real experiments can also lie between these two extremes.
> If a detector provides only partial information about the path, the interference pattern may become weaker rather than disappearing completely.
> For this introductory lecture, we focus on the two clearest cases: no path information and perfect path information.

25 Does the Electron "Know" We Are Watching?

No.
The electron does not need to know anything about a scientist, detector, computer, or observer.
The apparatus physically interacts with the quantum system.
That interaction can make the two paths distinguishable.

> **Check Your Understanding**
>
> A detector records which slit each electron used, but nobody ever reads the detector.
> Does the original interference pattern return simply because no person looked at the data?
>
> **Answer: No.**
> The relevant physical interaction and path record already exist. Human consciousness is not required.

26 Did the Electron "Really" Use One Slit?

This question needs careful language.
If we actually measure the path, the detector gives a definite result:

$$S_1 \qquad \text{or} \qquad S_2.$$

But when we do **not** measure the path, simply assuming that the electron secretly took one definite classical path leads to the wrong probability rule.

If it were only an unknown classical choice, we would expect

$$P_{12} = P_1 + P_2.$$

But experimentally we obtain interference.

Therefore, quantum mechanics tells us to use both path amplitudes:

$$\psi_1 + \psi_2.$$

It is better at this stage to say

"The quantum description contains amplitudes for both paths"

than to picture the electron as a tiny classical ball secretly taking one path while we simply do not know which one.

Different interpretations of quantum mechanics sometimes use different language about what is "really happening" between measurements.

The experimental prediction we need today does not depend on choosing one of those interpretations.

27 Now Superposition Has a Concrete Meaning

We are finally ready for the word

superposition.

Suppose the two possible paths are represented by

$$|\text{path 1}\rangle \qquad \text{and} \qquad |\text{path 2}\rangle.$$

The symbols $|\cdot\rangle$ are simply labels for quantum states.

A quantum state can contain an amplitude for each alternative:

$$|\psi\rangle = \alpha|\text{path 1}\rangle + \beta|\text{path 2}\rangle.$$

The numbers α and β are probability amplitudes.

This is a **superposition** of the two path states.

Big Idea

A superposition does **not** simply mean

"one classical answer has already happened, but we do not know which."

The amplitudes associated with the alternatives can later interfere.
That interference is what distinguishes quantum superposition from ordinary uncertainty.

28 A Closed Coin Is Not a Qubit

Suppose I flip a coin and cover it before you see the result.
You do not know whether it is

heads or tails.

But the coin already has one classical outcome.
Your lack of knowledge does not cause heads and tails to interfere.
That is **classical uncertainty**.
Quantum superposition is different because the amplitudes associated with alternatives can be recombined and can reinforce or cancel.
This is why saying

“a qubit is just a bit whose value we do not know”

is incorrect.

29 From Two Paths to a Qubit

Now rename the two path states:

$$|\text{path 1}\rangle \longrightarrow |0\rangle$$

and

$$|\text{path 2}\rangle \longrightarrow |1\rangle.$$

Then our state becomes

$$\boxed{|\psi\rangle = \alpha|0\rangle + \beta|1\rangle.}$$

This is the standard mathematical form of a **qubit**.
Do not let the notation make the idea seem more complicated.
It simply says:

the state has an amplitude associated with 0 and an amplitude associated with 1.

When we measure the qubit, the result is

$$0 \quad \text{or} \quad 1.$$

Born’s probability rule gives

$$P(0) = |\alpha|^2$$

and

$$P(1) = |\beta|^2.$$

Because some outcome must occur,

$$\boxed{|\alpha|^2 + |\beta|^2 = 1.}$$

30 Double Slit and Qubit Side by Side

Double-Slit Language	**Quantum Information Language**
Path 1 and path 2	States $|0\rangle$ and $|1\rangle$
Amplitude for each path	Amplitude α and β
Both path amplitudes present	Superposition
Paths combine	Amplitudes can interfere
Which-path detector	Measurement
One detected result	One classical measurement outcome

The double-slit experiment is therefore not a historical detour.
It introduces the same logic that appears in quantum information processing.

31 Why Interference Matters for Quantum Computing

It is common to hear:

"A quantum computer tries every answer at the same time."

That explanation is incomplete and often misleading.
A measurement gives us only one classical outcome.
We cannot simply place many answers into a superposition and then read all of them.
The useful part is **interference**.
A quantum algorithm manipulates amplitudes so that, ideally,

$$\text{amplitudes of useful outcomes} \quad \longrightarrow \quad \text{reinforce}$$

while

$$\text{amplitudes of unwanted outcomes} \quad \longrightarrow \quad \text{partially cancel.}$$

That changes what we are likely to observe when we finally measure.

Big Idea

Superposition creates quantum alternatives.
Interference changes their amplitudes.
Measurement converts the final quantum state into an observed classical outcome.
These three ideas are central to quantum computing.

32 Where Schrödinger and Born Fit

We can now summarize two major rules of quantum mechanics without using advanced mathematics.

Between Measurements

The quantum state changes with time according to quantum dynamics. For the systems we study here, that evolution is described by the **Schrödinger equation**.

We will study its mathematics later.

For now, think:

$$\boxed{\text{Schrödinger} \longrightarrow \text{how quantum amplitudes evolve.}}$$

When We Measure

The possible outcomes occur with probabilities determined by the amplitudes.

Think:

$$\boxed{\text{Born} \longrightarrow \text{how amplitudes give measurement probabilities.}}$$

These two ideas explain why quantum mechanics can evolve amplitudes very precisely while individual measurement outcomes remain probabilistic.

33 The Entire Experiment in One Table

Experiment	**Rule**	**What appears on the screen?**
Classical particles	$P_{12} = P_1 + P_2$	Two ordinary particle distributions
Classical waves	Combine amplitudes first	Alternating reinforcement and cancellation
Electrons, path not measured	$P_{12} = \lvert\psi_1 + \psi_2\rvert^2$	Individual dots gradually form an interference pattern
Electrons, perfect path measurement	$P_{\text{measured}} = P_1 + P_2$	Two-path interference disappears

34 Common Misconceptions

Misconception 1 – "The electron splits into two half-electrons."
No. A detector records a complete electron as one localized event. Quantum mechanics assigns probability amplitudes to the alternative paths.

Misconception 2 – "Each electron lands in several places."
No. Each electron produces one localized detection. The interference pattern appears only after many detections are accumulated.

Misconception 3 – "Different electrons interfere with each other."
That cannot explain the effect. The interference pattern can build up when individual electron detections are well separated in time.

Misconception 4 – "A human observer changes the experiment by looking."
No. Human consciousness is unnecessary. A physical interaction that records which-path information is what matters.

Misconception 5 – "Superposition simply means we do not know the answer."
No. Ordinary uncertainty does not produce interference. Quantum probability amplitudes can reinforce and cancel.

Misconception 6 – "An electron is literally a classical particle and a classical wave at the same time."
Neither classical picture is sufficient. Electrons are quantum objects whose detection events and probability patterns exhibit features that classical particles or classical waves alone cannot fully describe.

35 Recitation – Explain It Without the Notes

Check Your Understanding

1. What happens when ordinary classical particles have two possible paths?

Their probabilities add:

$$P_{12} = P_1 + P_2.$$

2. What happens when two waves overlap?

They can reinforce or cancel, producing interference.

3. What does one electron look like when it reaches the detector?

It appears as one localized detection.

4. What happens after many electrons are sent through two available paths without determining the path?

The individual detections gradually form an interference pattern.

5. What interferes in the quantum description?

Probability amplitudes.

6. What is the basic quantum rule for two alternatives?

$$P_{12}(x) = |\psi_1(x) + \psi_2(x)|^2.$$

Add amplitudes first, then determine probabilities.

7. What happens when we perfectly determine which path was taken?

The two-path interference disappears.

8. Does measurement require a conscious person?

No. Measurement involves a physical interaction and a physical record.

9. Why is superposition different from ordinary uncertainty?

Quantum alternatives have amplitudes that can interfere. Classical uncertainty does not.

36 Five Things You Must Remember

Big Idea

1. **Each electron is detected at one location.**
2. **Many electron detections can build an interference pattern.**
3. **Quantum alternatives combine through probability amplitudes.**

$$P_{12} = |\psi_1 + \psi_2|^2.$$

4. **Perfect which-path information removes the original two-path interference.**
5. **The same ideas lead directly to superposition, interference, measurement, and qubits.**

37 The One Sentence to Remember

A quantum object can arrive as one localized detection while the probability of where it arrives is determined by amplitudes that can interfere.

One-Minute Exit Check

Complete these without looking back.

1. Ordinary classical particle alternatives combine by adding ____________.
2. Waves can reinforce and ____________ one another.
3. Quantum alternatives combine by adding ____________.
4. The quantity $|\psi|^2$ gives ____________ information.
5. A perfect measurement of which path was taken removes ____________.
6. A human observer is ____________ for quantum measurement.
7. The two-path experiment provides a concrete example of quantum ____________.

Answers: probabilities; cancel; probability amplitudes; probability; interference; unnecessary; superposition.

Historical and Pedagogical Acknowledgments

These notes acknowledge the scientific contributions of **Leucippus and Democritus** to early atomistic thought; **Thomas Young** to the experimental study and principle of optical interference; **Louis de Broglie** to the matter-wave hypothesis; **Erwin Schrödinger** to wave mechanics; **Max Born** to the statistical interpretation of the wavefunction; **Clinton Davisson, Lester Germer, and George Paget Thomson** to the experimental demonstration of electron diffraction; **Claus Jönsson** to electron interference using fabricated slits; **Pier Giorgio Merli, Gian Franco Missiroli, and Giulio Pozzi** to experimental studies of individual-electron interference buildup; **Akira Tonomura, J. Endo, T. Matsuda, T. Kawasaki, and H. Ezawa** to the widely known single-electron buildup demonstration; and **Roger Bach, Damian Pope, Sy-Hwang Liou, and Herman Batelaan** to the controlled double-slit electron experiment.

The particles–waves–electrons–which-path teaching sequence used throughout these notes is inspired in part by the influential presentation of **Richard P. Feynman, Robert B. Leighton, and Matthew Sands** in *The Feynman Lectures on Physics, Volume III* [10].

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