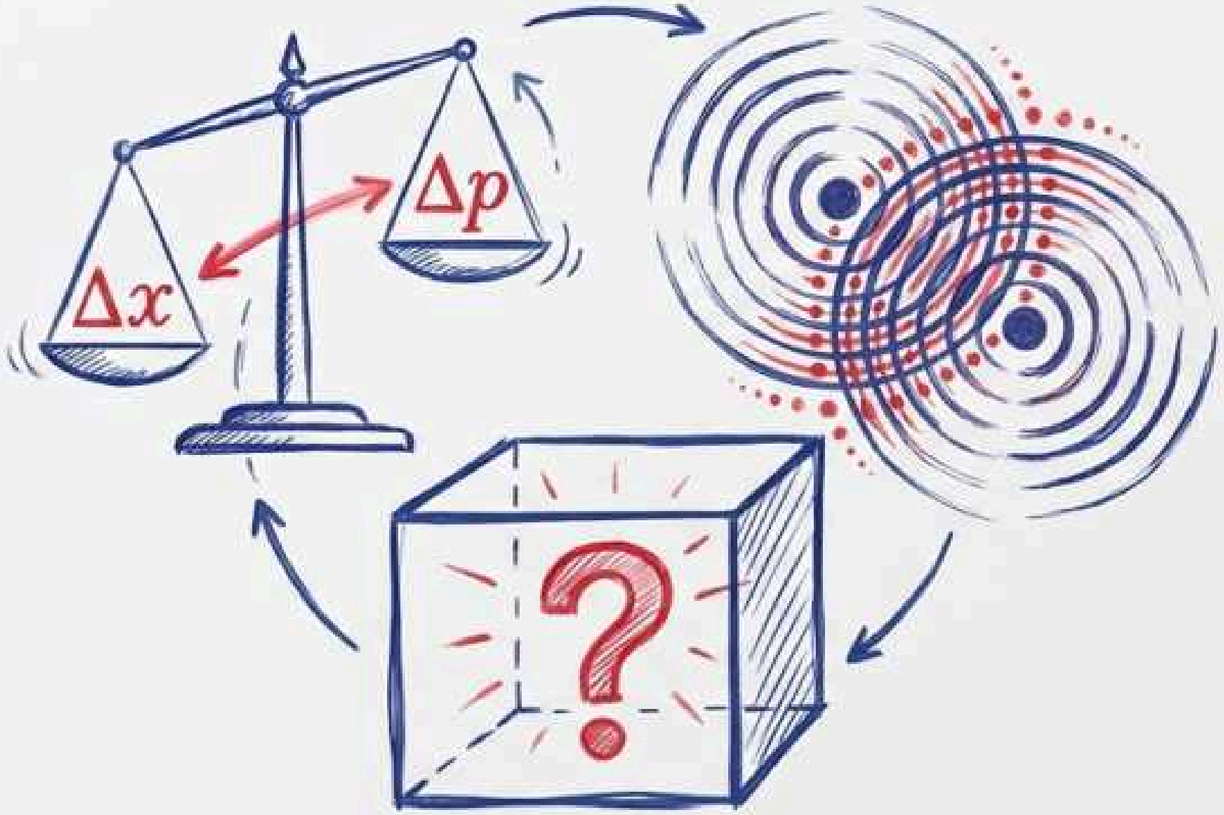
PHYS 220 B Lecture 4

Uncertainty, Superposition and Measurement



The deepest mysteries of the universe, sketched out.

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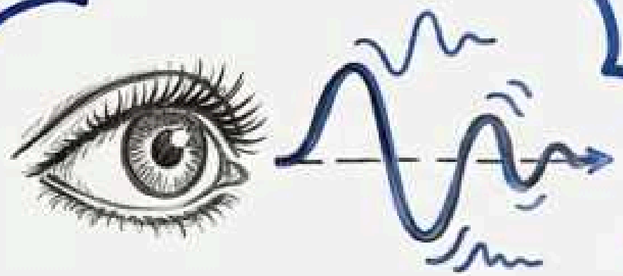
[4.1] | Three Quantum Questions

$\geq$

What exactly does Heisenberg's uncertainty principle say, and why is it true?



What does it mean for something to be in a superposition?



What happens when we make a measurement, a question that still divides physicists today?

[4.2] | The Limit of Precision (1927)

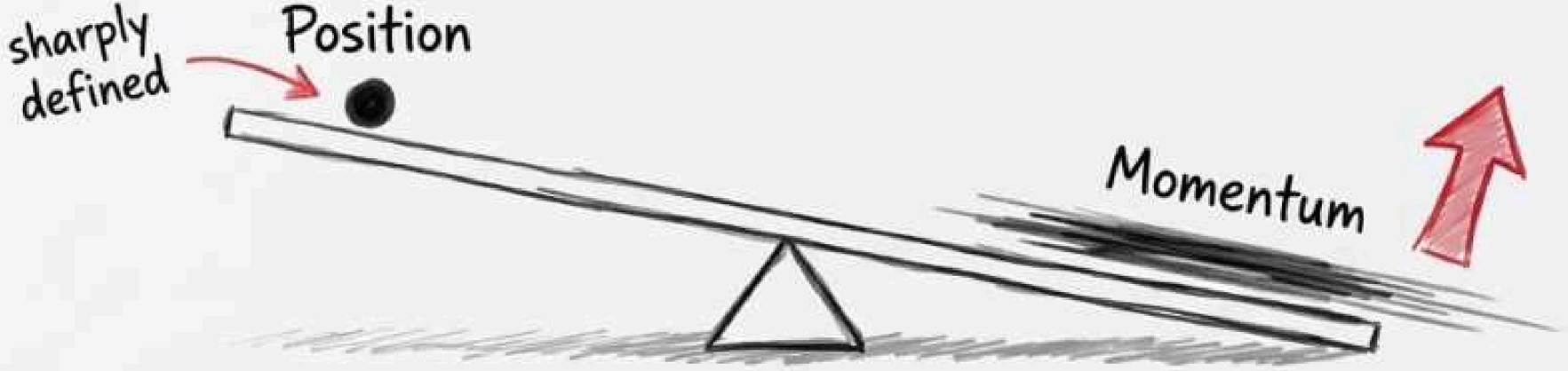
$$\Delta x \cdot \Delta p \geq \frac{\hbar}{2}$$

Spread in a particle's position

Spread in its momentum

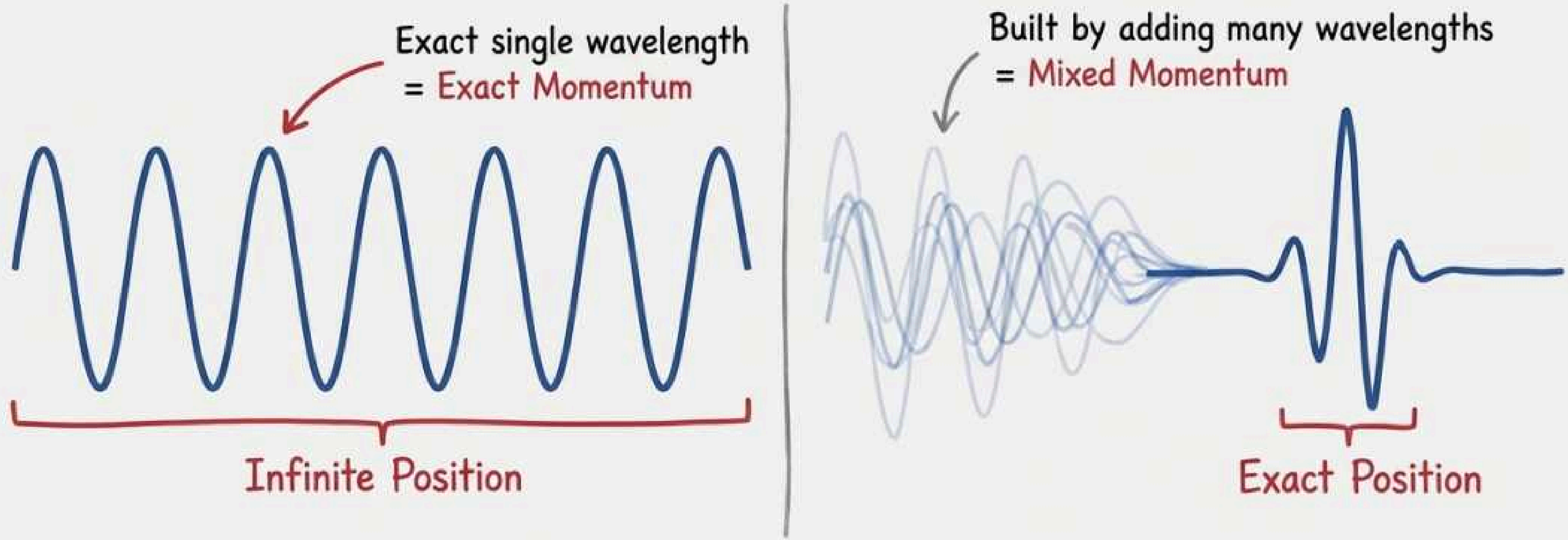
$\hbar$ (h-bar) = $\frac{\text{Planck's constant}}{2\pi}$

($\approx 1.05 \times 10^{-34}$ joule-seconds)



The more sharply one is defined, the more spread out the other must be.

[4.3] | Uncertainty is a Wave Property



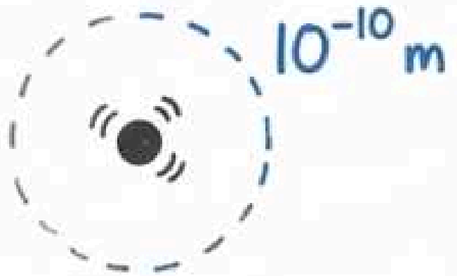
Not just clumsiness (light kicking an electron).

A short pulse (like a sharp hand clap) has a definite position but no single momentum.

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[4.4] | A Tale of Two Scales

The Electron

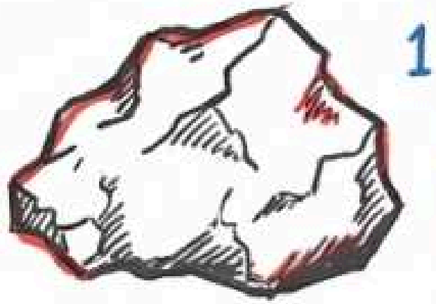


Confined space: 10^{-10} m

Spread in speed: $\geqslant 600$ km/s

Result: Electrons cannot sit still.

The Dust Grain



1 microgram mass, located within 1 micrometre

Confined space: 10^{-6} m

Spread in speed: 10^{-20} m/s

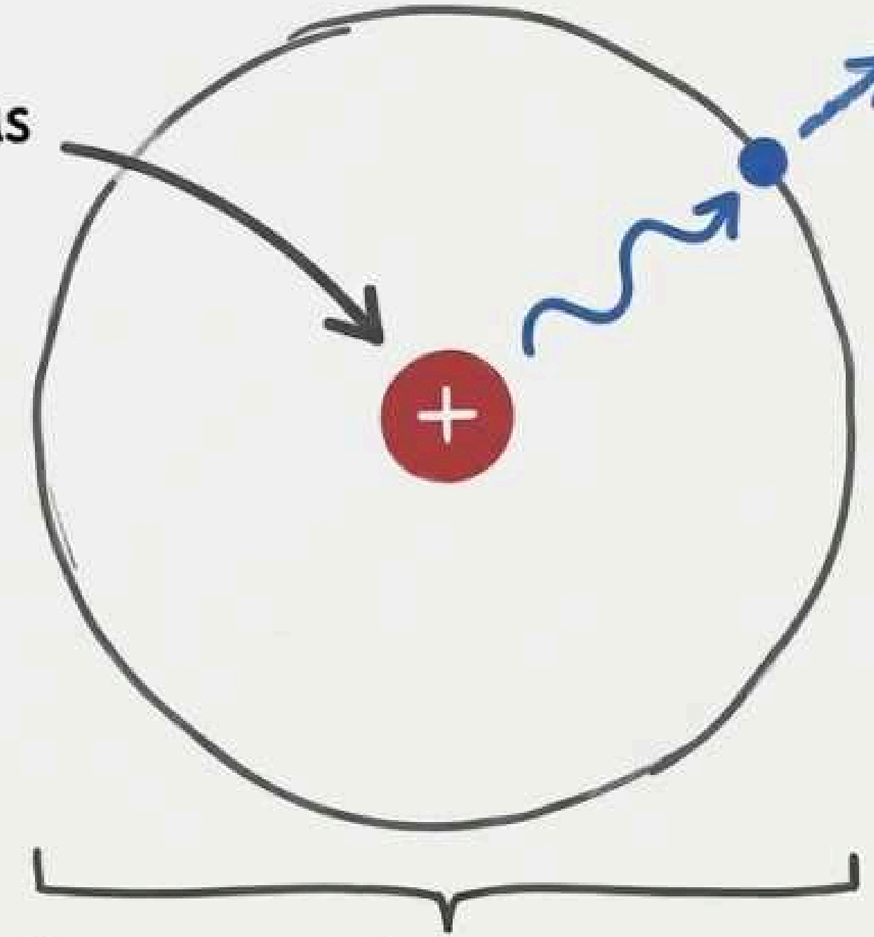
Result: Far too small to notice.

"Protects" quantum mechanics: no one has found a way to beat it. – Richard Feynman

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[4.5] | Why Atoms Have Size

Electric pull of nucleus tries to squeeze electron closer.



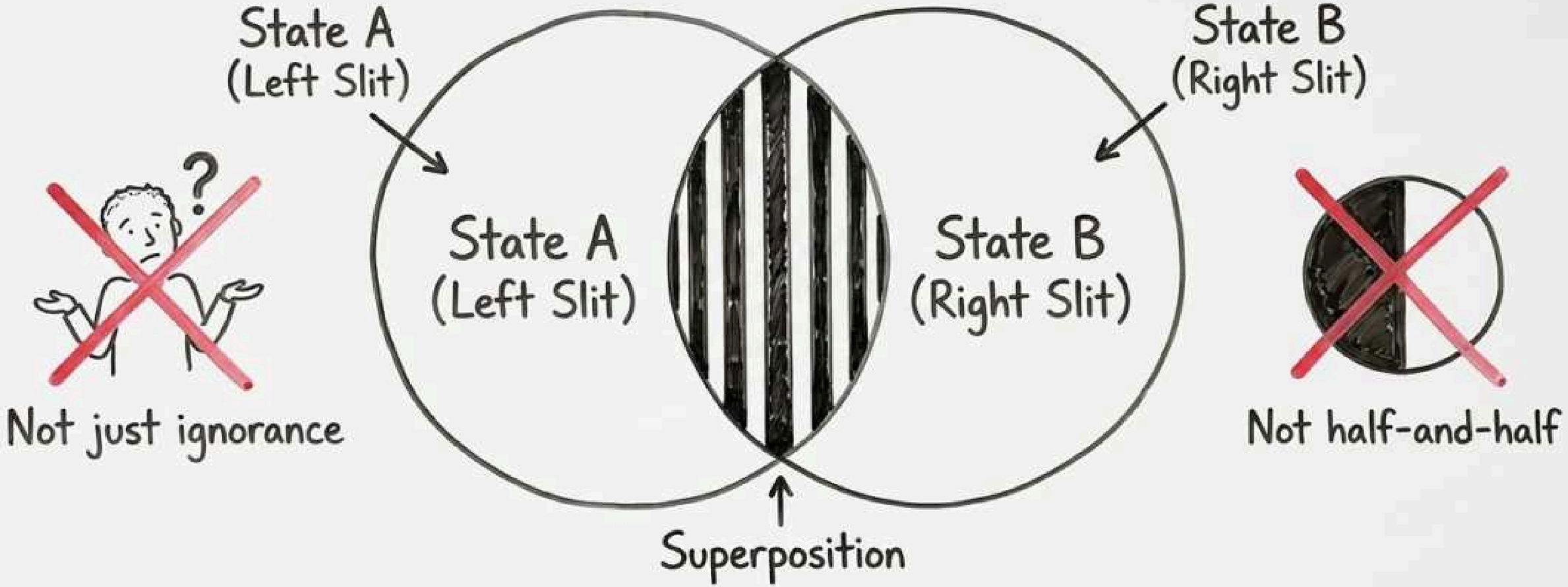
Uncertainty Principle: Squeezing raises momentum spread, forcing it outward.

The atom settles where these two effects balance.

Hydrogen: ≈ 0.1 nanometres across.

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[4.6] | The Reality of Superposition



Not just ignorance

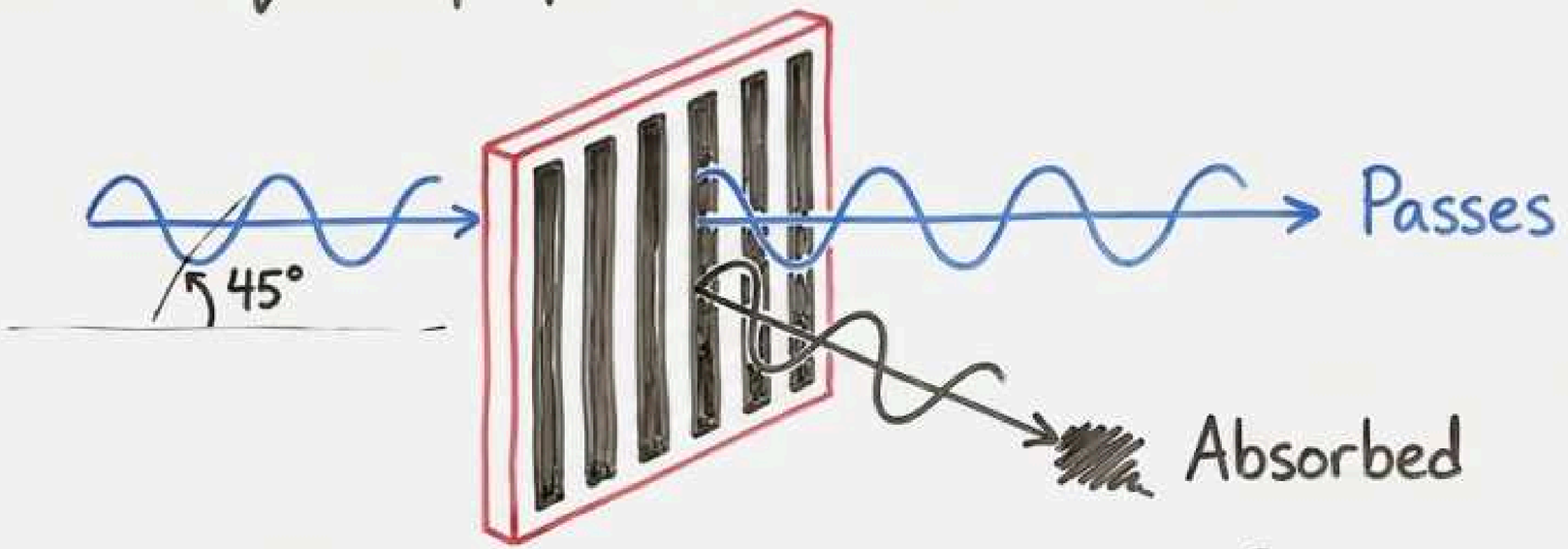
Not half-and-half

If a system can be in State A, and can be in State B, it can be in a combination of the two.
A genuinely new kind of state that allows paths to interfere.

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[4.7] | A Clean Example: Polarized Light

Photon at 45° = Equal superposition of vertical and horizontal.



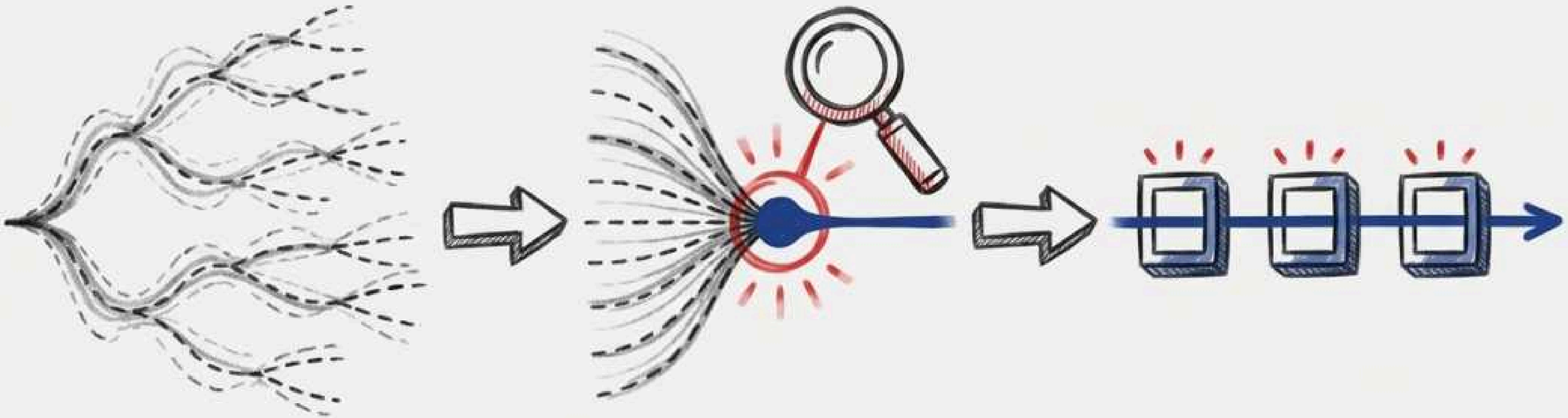
It either passes or is absorbed.
Never half of each.

Over many photons,
exactly half pass.

Chance of passing = $\cos^2\theta$

[4.8] | The Pattern of Measurement

Before → The Event → After



Theory predicts probabilities via Born rule.

Measurement yields one sudden, definite outcome.

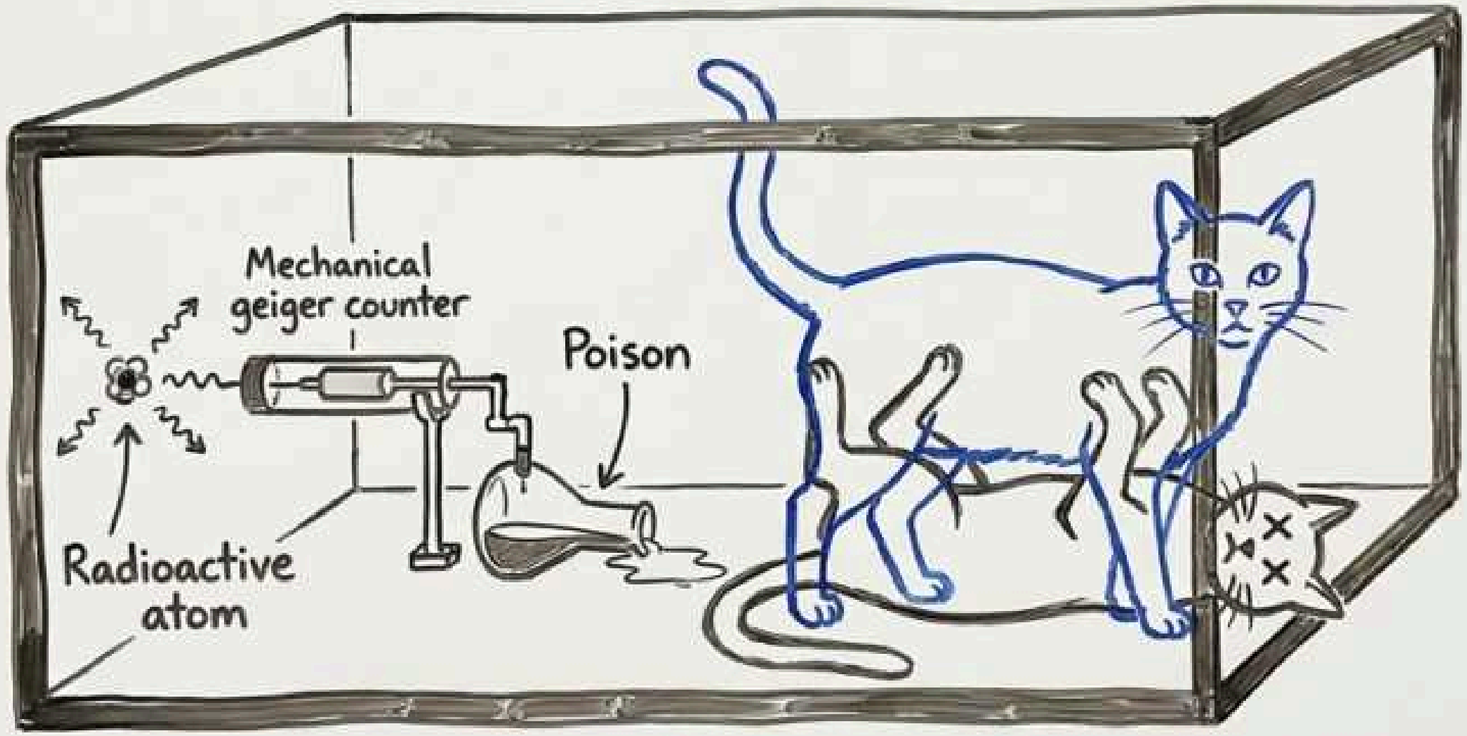
System behaves as matching state—the "collapse of the wavefunction".

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[4.9] | Schrödinger's Cat (1935)

If rules of superposition apply all the way up...

System is in a superposition of a living cat and a dead cat until someone looks.



Intended as a CRITICISM! Shows the absurdity of applying quantum theory to everyday objects without an ending point.

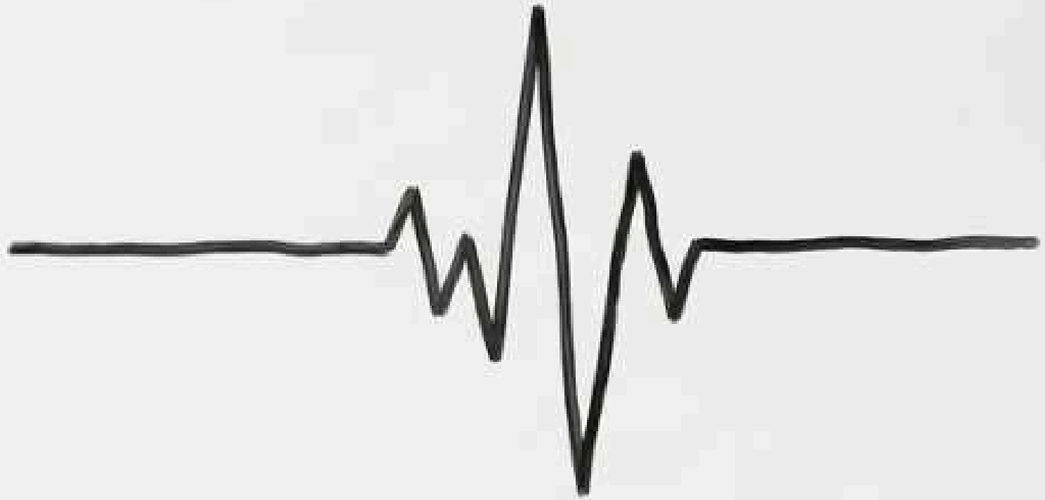
[4.10] | The Measurement Problem

No one is looking

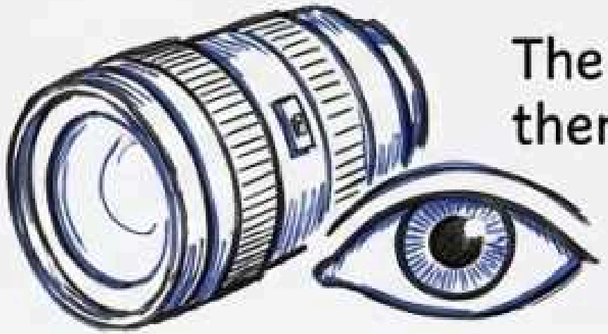


Rule 1: Smooth change (Schrödinger's equation). Superpositions persist.

A measurement is made



Rule 2: Sudden, random outcome appears.



The Core Puzzle: Measuring devices are themselves made of atoms. So what counts as a measurement, and why does it obey a different rule?

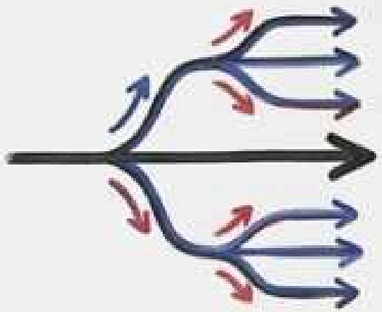
[4.11] | Four Interpretations

Copenhagen



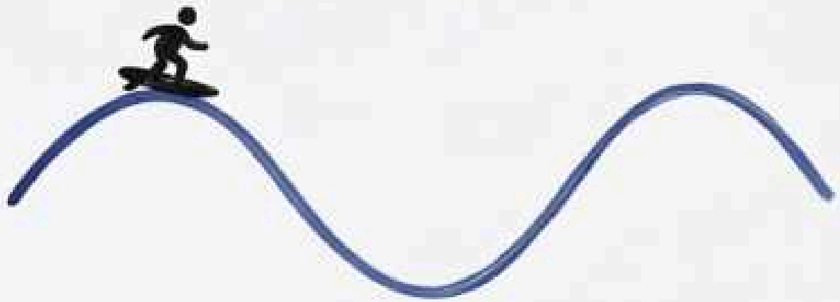
Bohr/Heisenberg: Wavefunction is a tool for predicting results, not a picture of hidden reality.

Many-Worlds



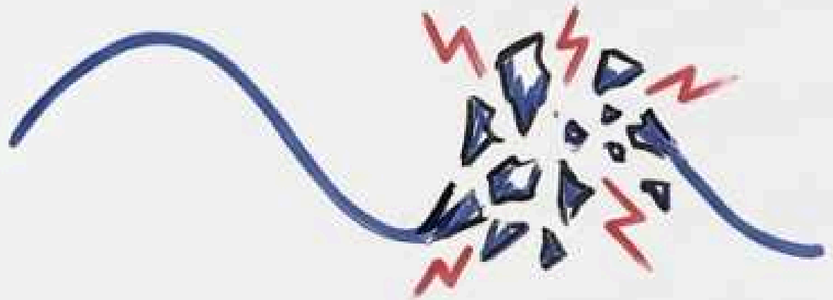
Everett (1957): Wavefunction never collapses. Every outcome happens in its own branch.

Pilot-Wave



Bohm (1952): Particles always have definite positions, guided by the wave.

Collapse Theories

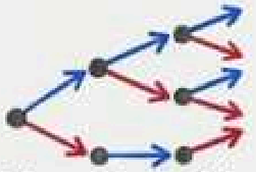


Equations are modified so large superpositions break down on their own.

[4.12] | The Pragmatic Reality



Copenhagen



Many-Worlds

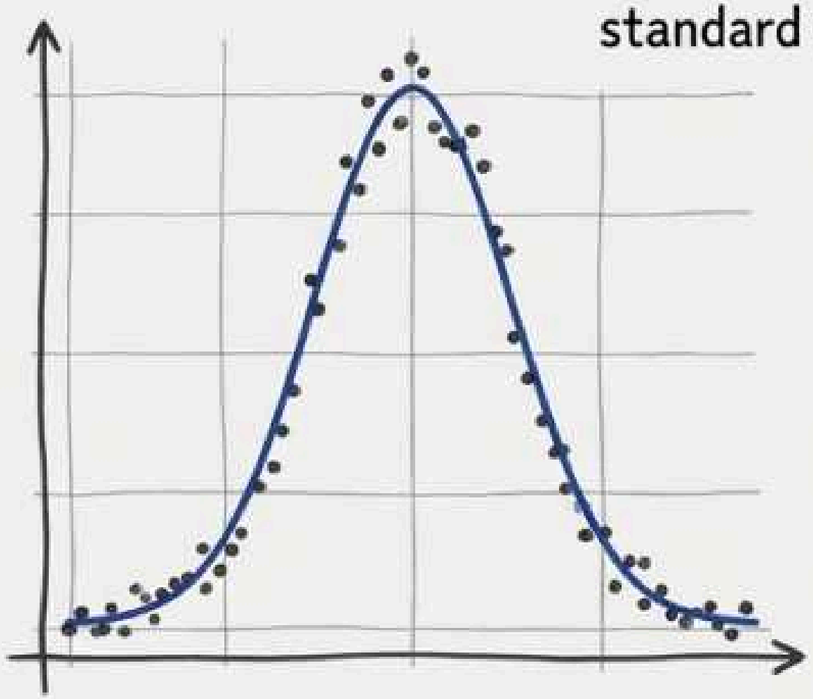


Pilot-Wave



Collapse Theories

Every major interpretation reproduces the predictions of standard quantum mechanics.



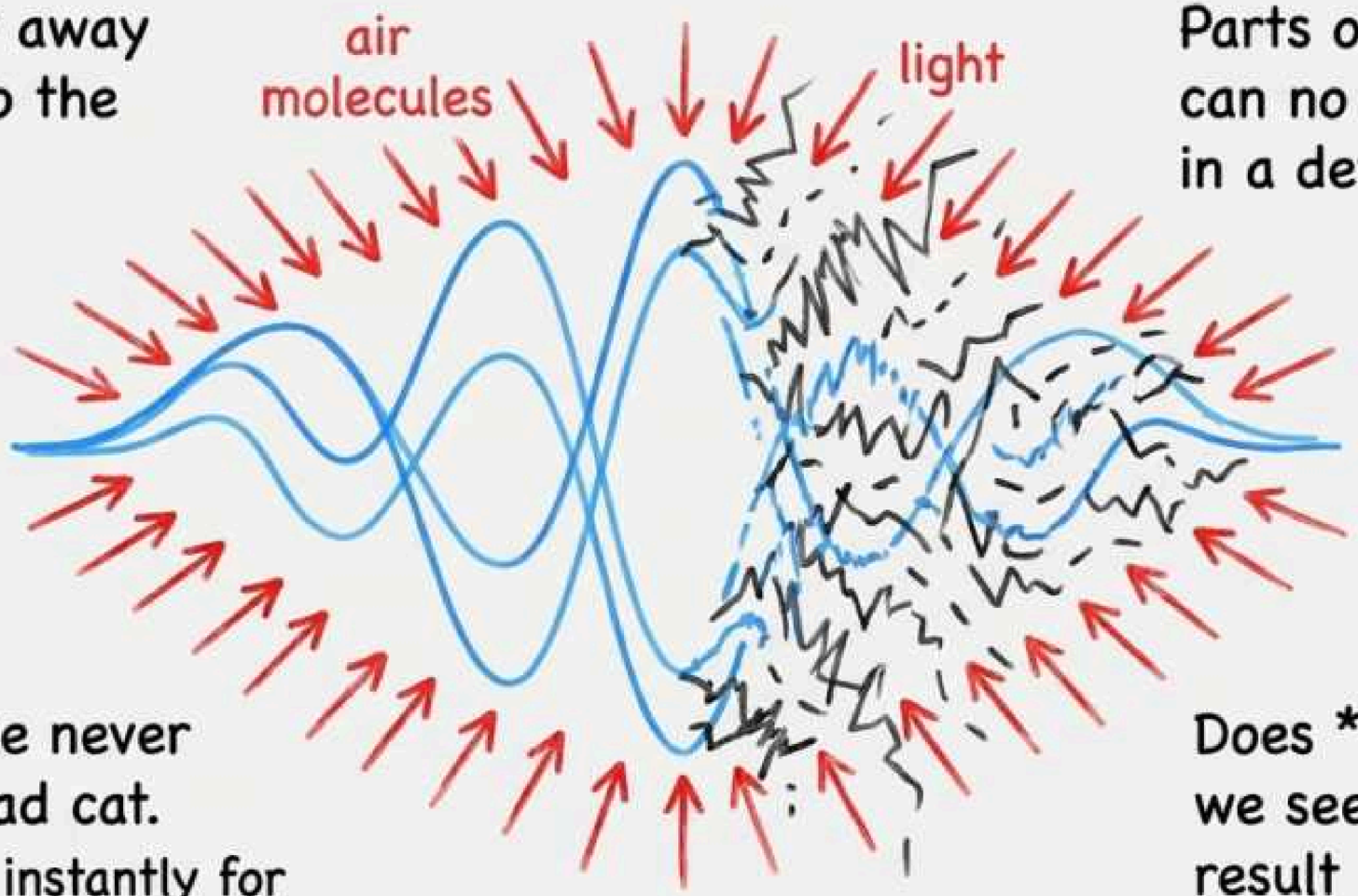
For everyday use, all physicists calculate in the exact same way.

The disagreement is about what the calculations *mean*.

Note: Collapse theories differ slightly in principle; experiments are searching for those differences.

[4.13] | Decoherence (Zurek 2003)

Collisions carry away information into the surroundings.

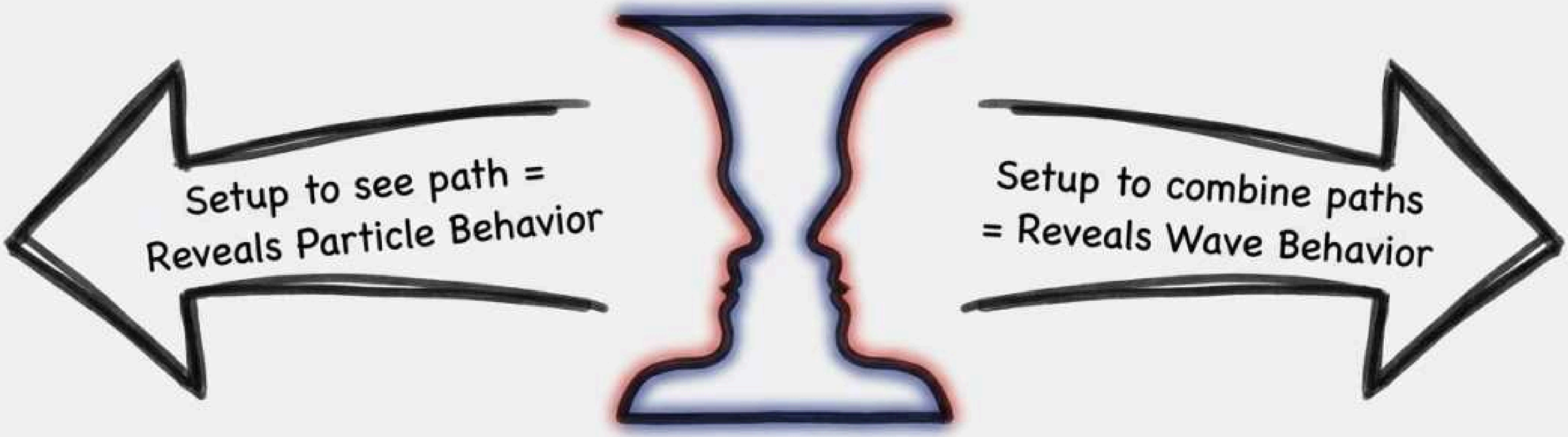


Parts of a superposition can no longer interfere in a detectable way.

Explains why we never see a living/dead cat.
(Happens almost instantly for anything as large as a dust grain).

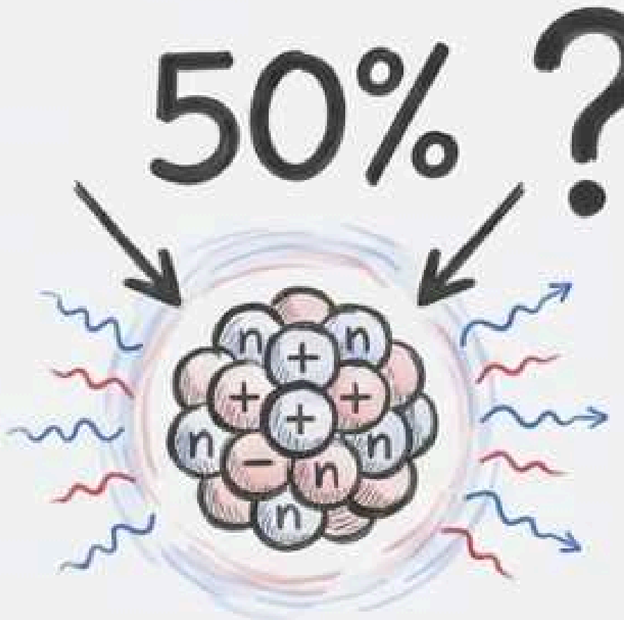
Does *not* explain why we see one particular result over another.

[4.14] | Bohr's Complementarity



- The two arrangements mutually exclude each other.
- A complete description needs both.
- Position and momentum are complementary in the exact same way (Uncertainty Principle). ~ Heisenberg's relation, $\Delta x \cdot \Delta p \geq \frac{\hbar}{2}$

[4.15] | Genuine Quantum Randomness



We know there is a 50% chance of decay within a half-life, but cannot predict *_when_*.

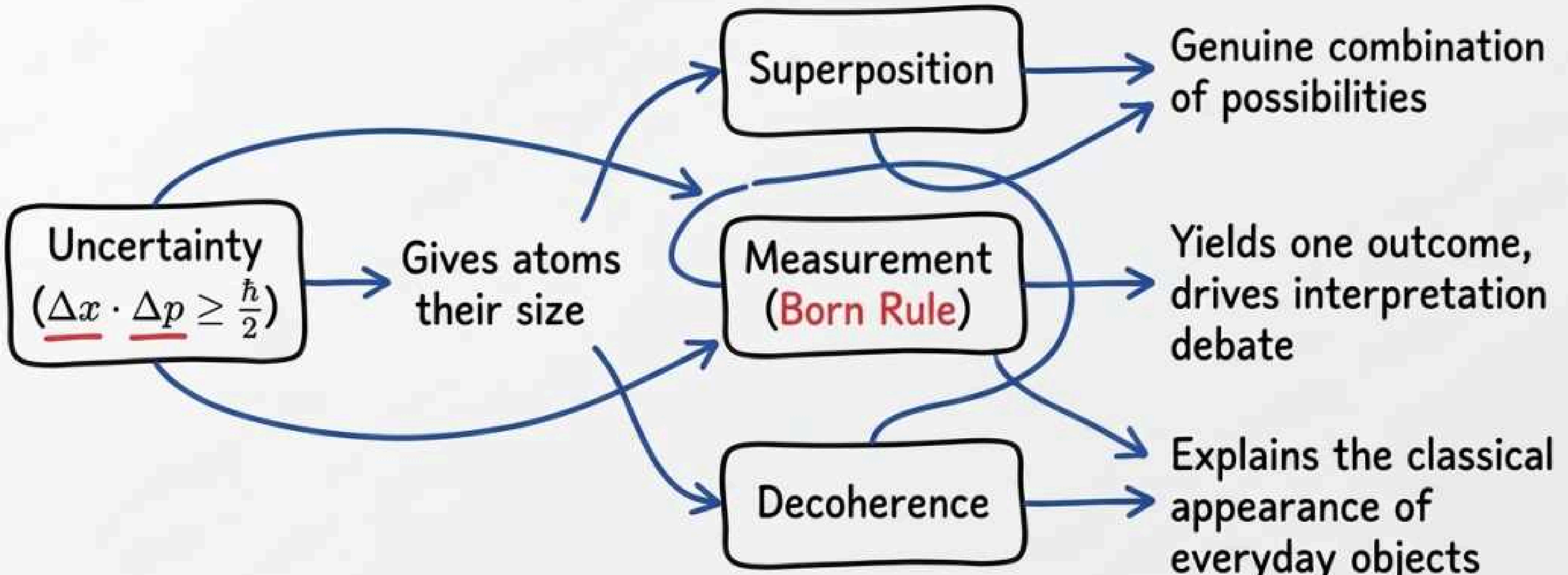


"God does not play dice."
— Einstein (in letters to Max Born)

Today: Quantum random number generators use this exact unpredictability for secure computing.

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[4.16] | The Quantum Rules Summary



Matter has wave nature.

Next Lecture: Spin and Entanglement.