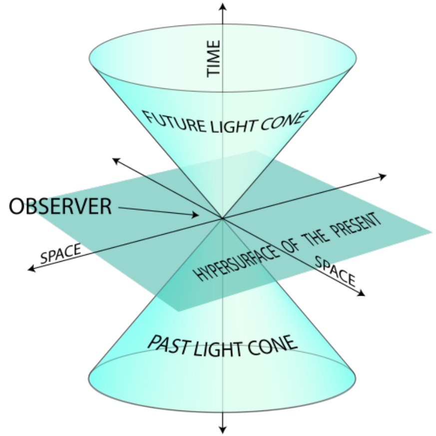
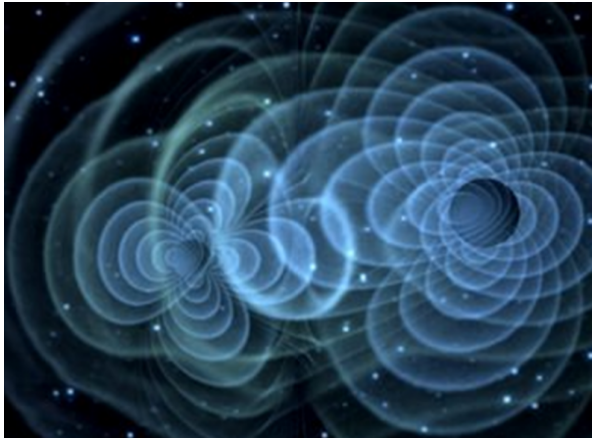
- Modern physics is about **unifications**:
  - Special relativity: space + time → spacetime
  - General relativity: spacetime + gravity → curved spacetime
  - Quantum mechanics: wave + particle → quantum particle

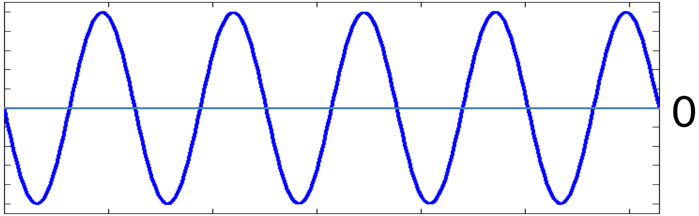




We will begin with some simple experiments with **light**

These experiments have **profound consequences** for the ultimate nature of reality

Reality is **much stranger** than anyone in human history ever imagined it could be

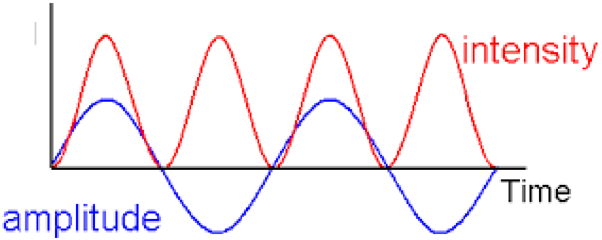


Amplitude = height of wave: positive for a crest, negative for a trough, zero for no wave

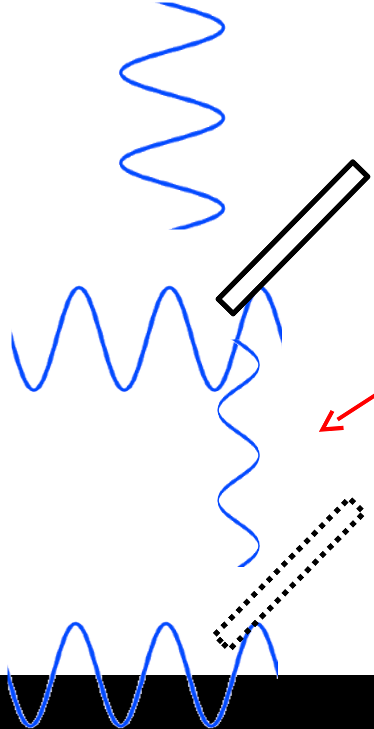
Interference: Two overlapping waves will add:

- crest + crest = double-amplitude crest
  $(1 + 1 = 2)$
- trough + trough = double-amplitude trough
  $(-1 - 1 = -2)$
- crest + trough = zero amplitude
  $(1 - 1 = 0)$

Light behaves like a wave



Intensity = square of amplitude. This is related to the **energy** carried by the wave.

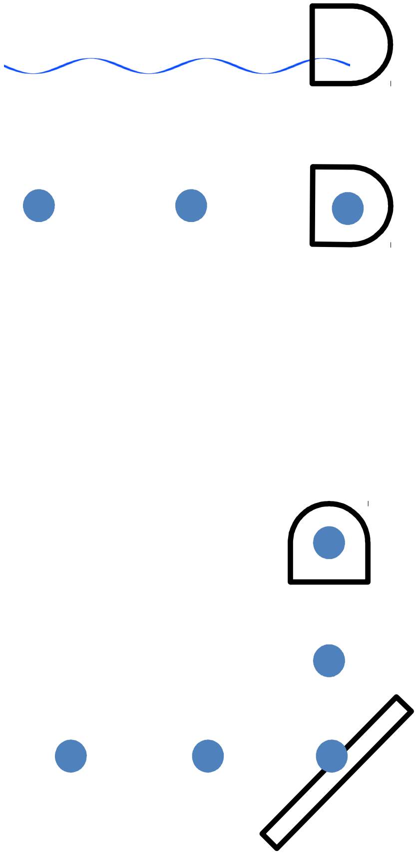


Light waves will **reflect** off a mirror

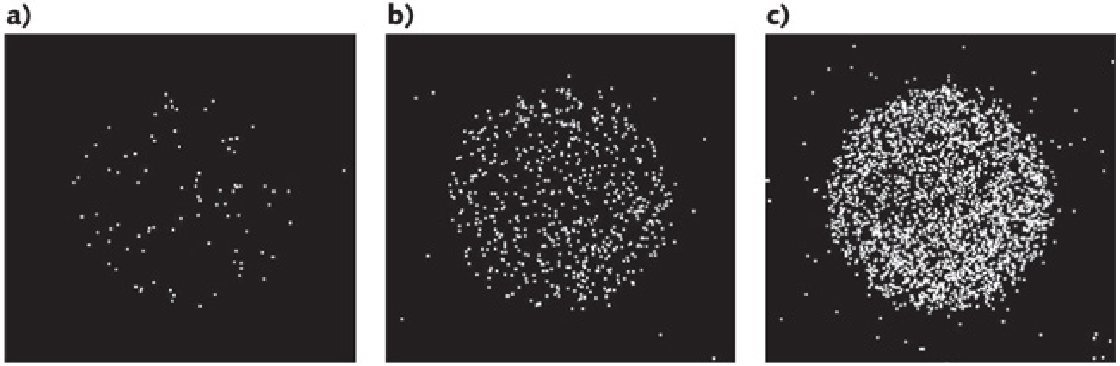
50% intensity (energy split in half—energy is conserved!)

Partial reflection and **partial** transmission through a “half-silvered mirror” = “beam splitter”

Light also behaves like a particle



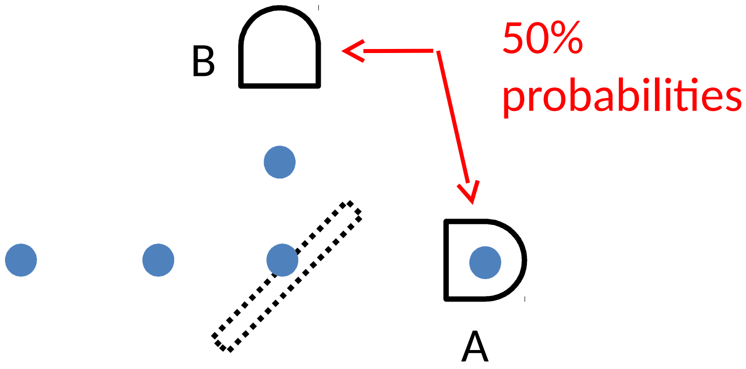
At very **low intensity**, a light detector will register the arrival of localized ‘bundles’ of energy ▭ Light behaves like a ‘shower’ of particles, called “photons”:



Images of a luminescent disk. Increased exposure time allows more photons to register in the detector

These particles will also reflect off a mirror

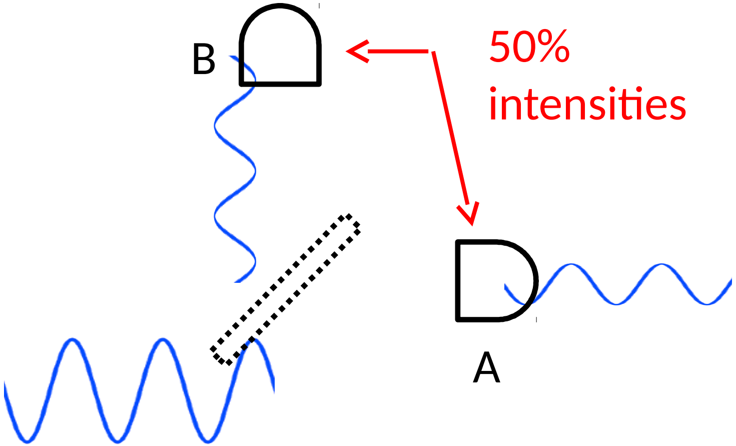
But there’s something weird about these particles



Detectors register a **full** photon, or **nothing**, with 50/50 probability (photon doesn’t split into two ‘half photons’)

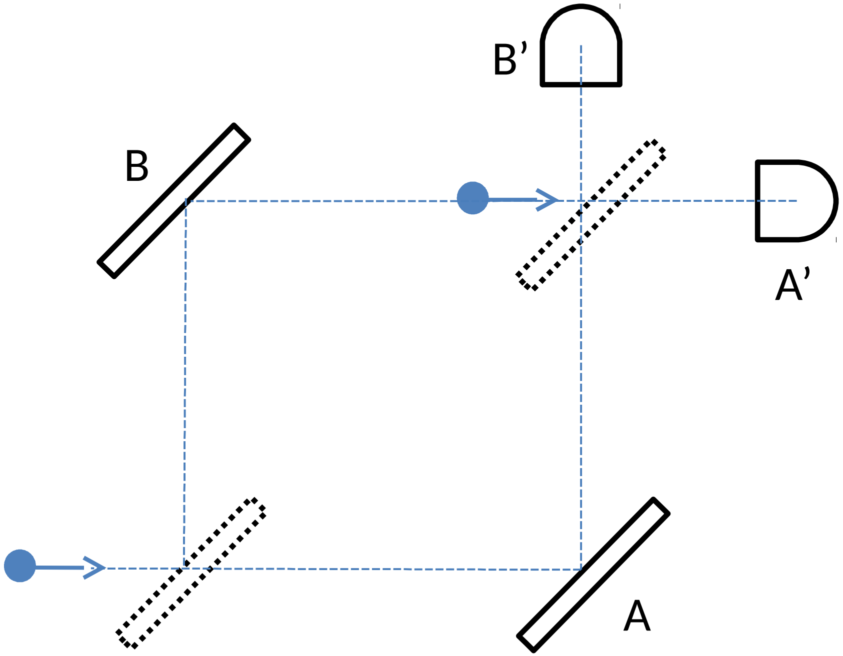
particle probability = wave intensity

But how does a photon ‘**decide**’ to reflect or transmit? *Appears* to be a **fundamental randomness** in nature…



Newtonian physics implies a deterministic “clockwork universe,” with no room for randomness (or free will, or ongoing God?). This appears to be a clear departure…

Einstein: “The theory produces a good deal but hardly brings us closer to the secret of the Old One. I am at all events convinced that *He* does not play dice.”



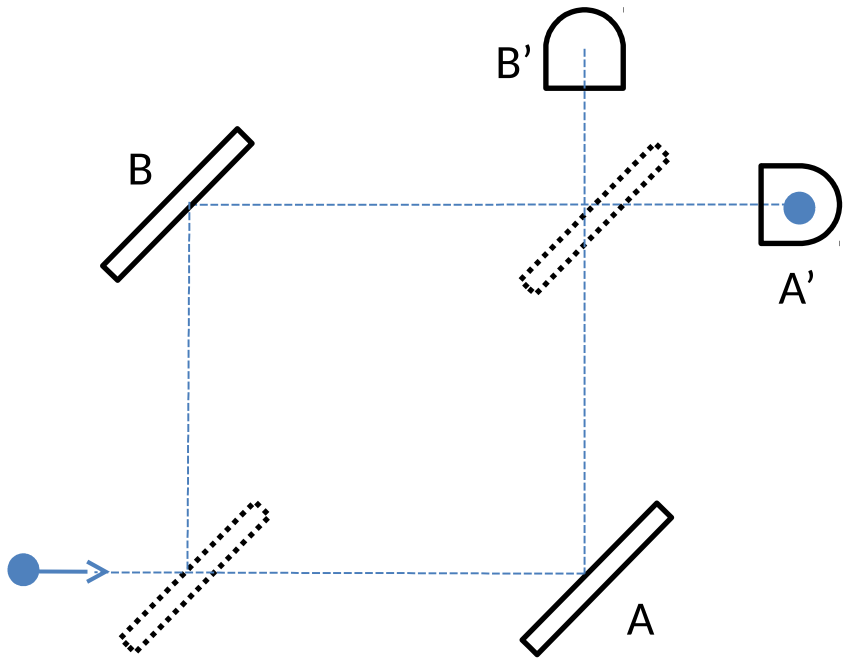
But it gets a lot weirder:

Suppose A and B replace their detectors with mirrors and we add a beam splitter and two new detectors, A’ and B’

Suppose at the first beam splitter the photon ‘chooses’ (50/50) to go up to B, and so travels along the upper path.

When it arrives at the second beam splitter, **what is the probability it continues on to A’? To B’? 50/50?**

What if it chooses the lower path? **50/50?**



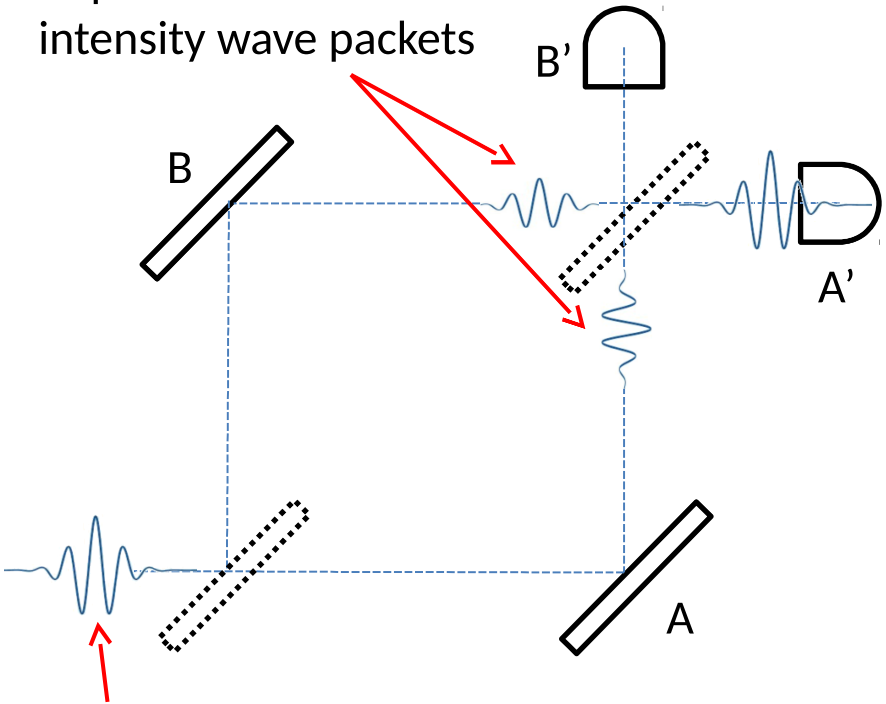
No! Any photons sent through this apparatus will *always* go to A', and *never* to B'!

100% probability for A'
0% probability for B'

How is this possible?

Photons are clearly **not** ordinary particles! There is *more* to their weirdness than just the random reflect/transmit 'decision'!

…splits into two **half**-intensity wave packets



Wave "packet" of a single photon…

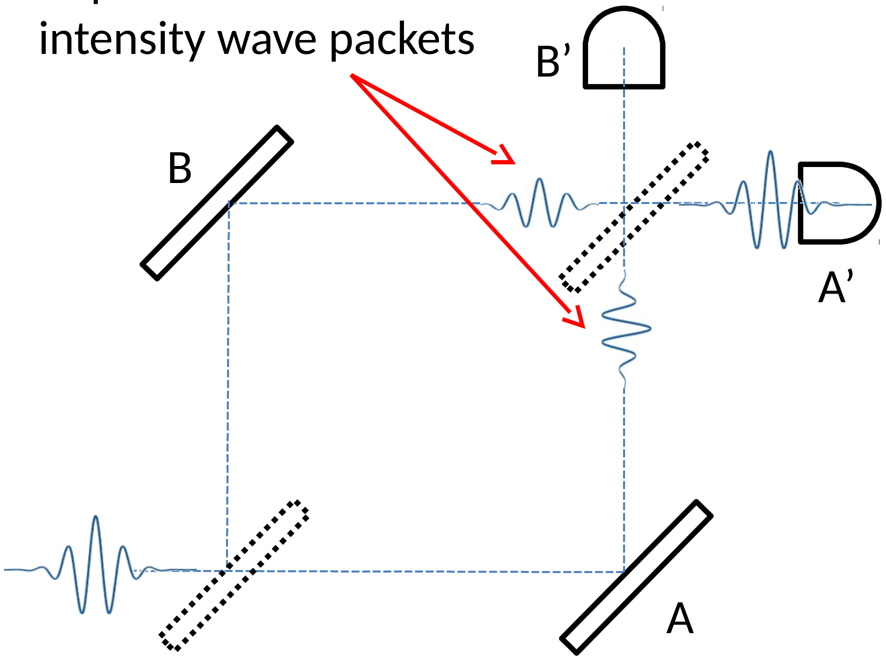
Let's go back to the wave picture:

At A' is a **half**-amplitude wave packet from B (transmitted through the second beam splitter) and a **half**-amplitude wave packet from A (reflected by the second beam splitter). These **interfere constructively** (half crest + half crest = full crest; similarly for troughs) to give the original **full**-amplitude wave packet:

…and hence **100% detection probability**.

Maybe the answer lies in the wave behavior of light…

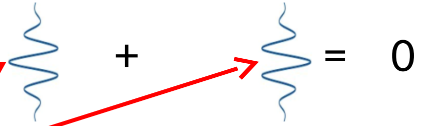
…splits into two **half**-intensity wave packets



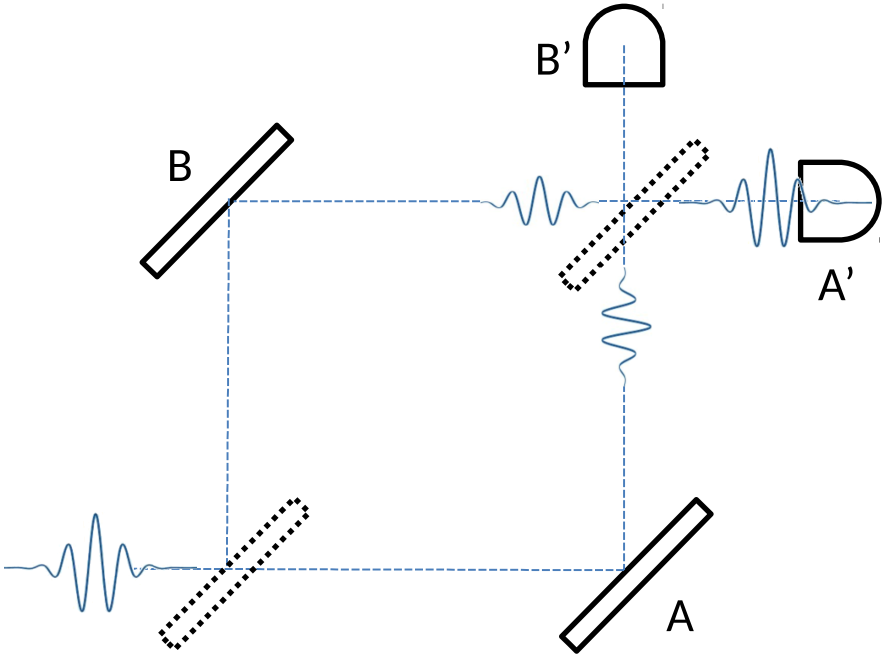
This peak is a crest on one, and a trough on the other, which *cancel* when added

Let’s go back to the wave picture:

At B’ is a **half**-amplitude wave packet from B (reflected by the second beam splitter) and the **half**-amplitude wave packet from A (transmitted through the second beam splitter). These **interfere *destructively*** (crest + trough = 0) to give **no** wave packet:



…and hence **0% detection probability**.

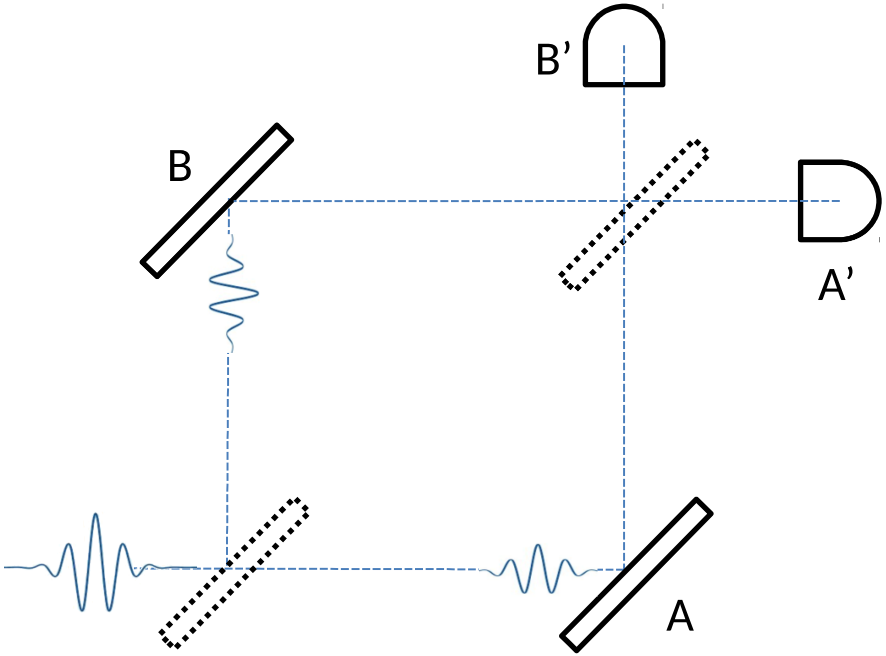


Summary: to explain

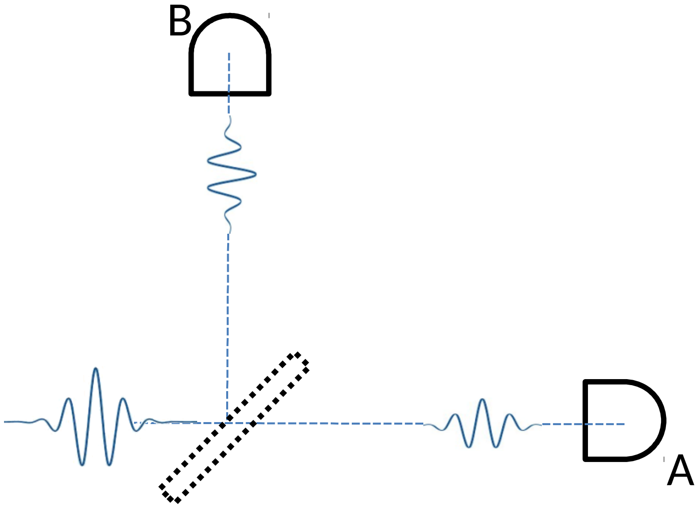
100% probability for A'
0% probability for B'

The ordinary-particle picture **fails**

The ordinary-wave picture **works**

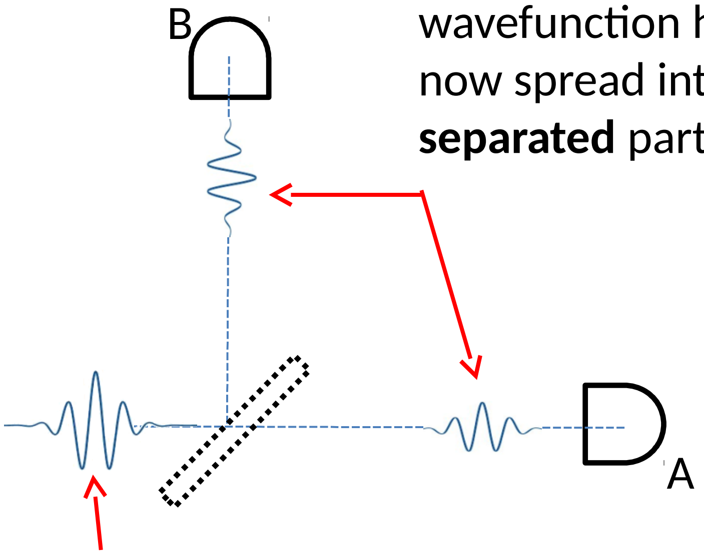


Let’s back up the experiment to where A and B are about to reflect the half-intensity wave packets…



Let’s back up the experiment to where A and B are about to reflect the half-intensity wave packets…

…and replace their mirrors with detectors (possibly at the ‘last minute’)



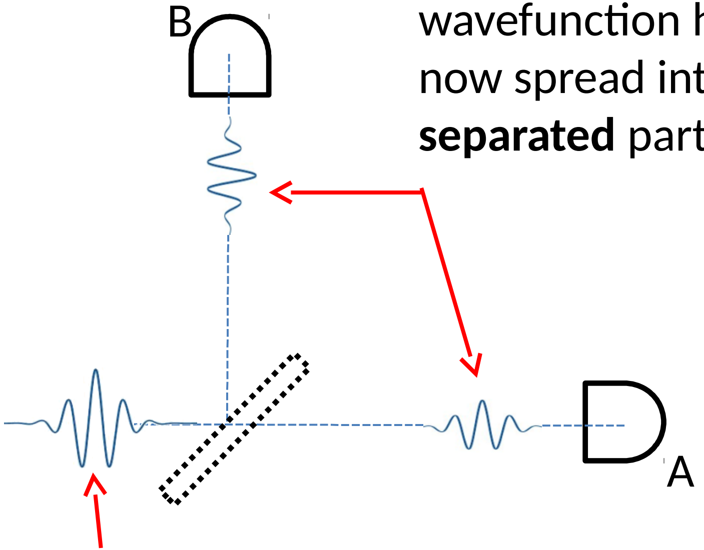
The one-photon wavefunction has now spread into two **separated** parts

Original "**wavefunction**" of the single photon

Let's back up the experiment to where A and B are about to reflect the half-intensity wave packets…

…and replace their mirrors with detectors (possibly at the 'last minute')

Note that the two **separated** parts of the wavefunction presumably don't 'know' what's coming up along their respective paths (mirror? detector? nothing?)



The one-photon wavefunction has now spread into two **separated** parts

Original "**wavefunction**" of the single photon

If these were **ordinary** waves, they would carry energy, and hence A and B **must** each register 'half' a photon

But they don't. A *or* B always detect a *full* photon (and the other nothing) with random 50/50 chance

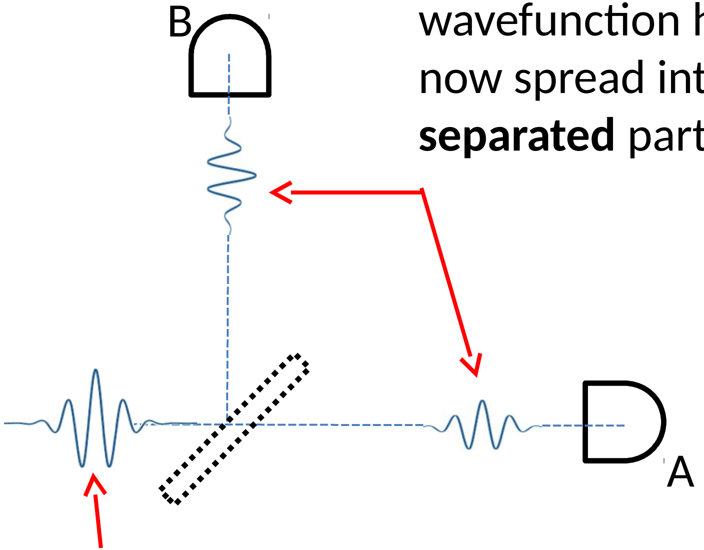
How is this possible? There is no way the energy of half a photon could **instantly** move between A and B (which could be light years apart)!

These are certainly **not** ordinary waves!

But there’s something weird about these waves…

The one-photon wavefunction has now spread into two separated parts

The one-photon wavefunction has now spread into two **separated** parts



Original “**wavefunction**” of the single photon

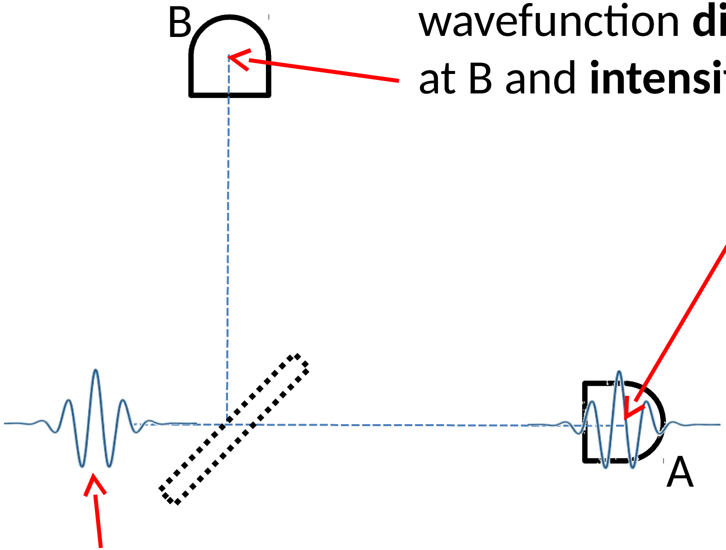
These waves have something to do with *probability*. Because the separated parts have only *half* the intensity, they predict 50% probability at A and 50% at B. But these are **not independent probabilities**:

If A detects the photon, B cannot, and vice versa. If A detects the photon, the probability the photon is at A suddenly jumps from 50% to 100%, and that at B suddenly jumps from 50% to 0%, even though A & B could be light years apart!

Wouldn’t this require some kind of ‘**instantaneous communication**’?!

The mysterious "wavefunction collapse"

The previously separated wavefunction **disappears** at B and **intensifies** at A



Original "**wavefunction**" of the single photon

Relatedly, there is "**wavefunction collapse**": if A detects the photon, the part of the wavefunction at A **intensifies** (as there is now a 100% probability the photon is at A), and at B it **disappears** (as there is now a 0% probability the photon is at B)

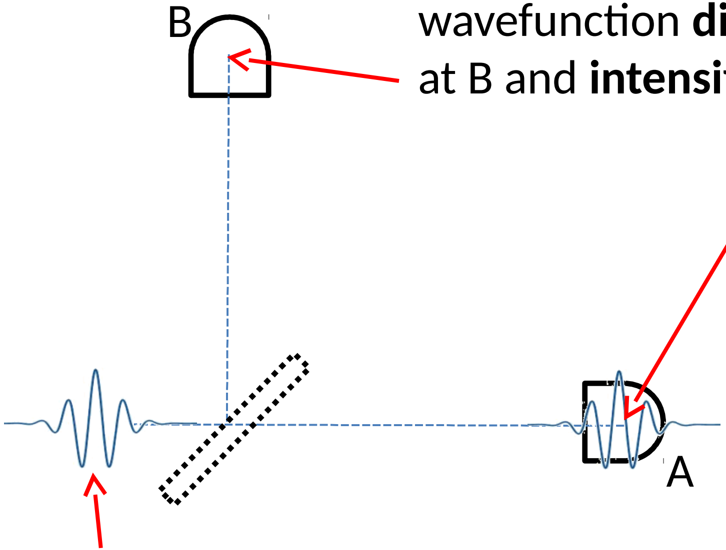
When a measurement is made at one location, it affects the wavefunction **everywhere**, no matter spread out it was

The wavefunction has a mysterious "**nonlocal**" or "**holistic**" character

These are certainly **not** ordinary waves!

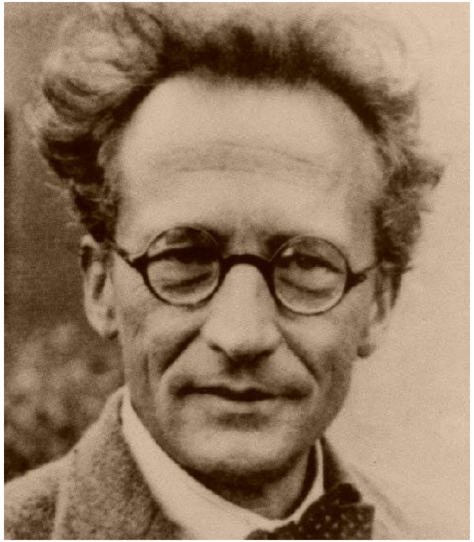
The mysterious “wavefunction collapse”

The previously separated wavefunction **disappears** at B and **intensifies** at A

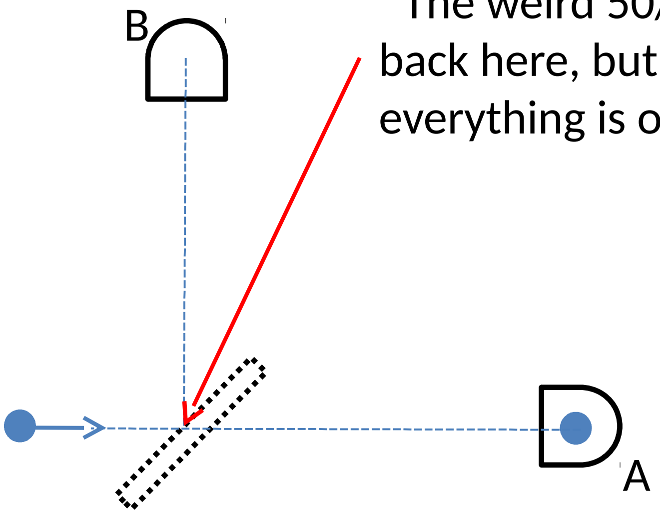


Original “**wavefunction**” of the single photon

Schrödinger:



“If all this damned quantum jumping [wavefunction collapse] were really here to stay then I should be sorry I ever got involved with quantum theory”



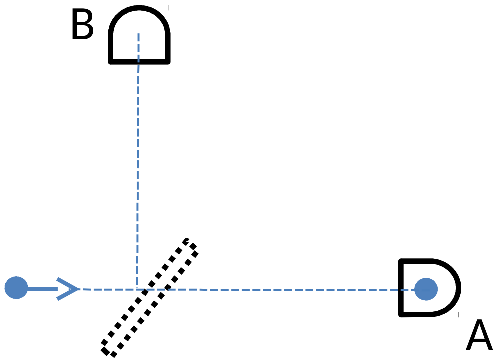
*The weird 50/50 is back here, but after that everything is ordinary

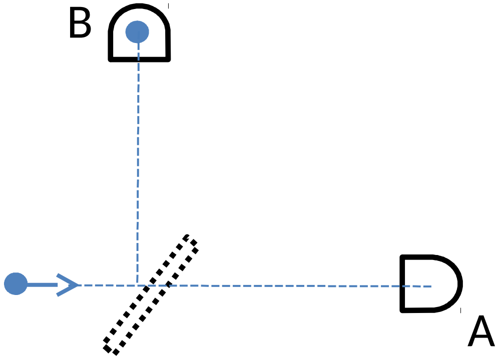
To explain:

50% probability for A
50% probability for B

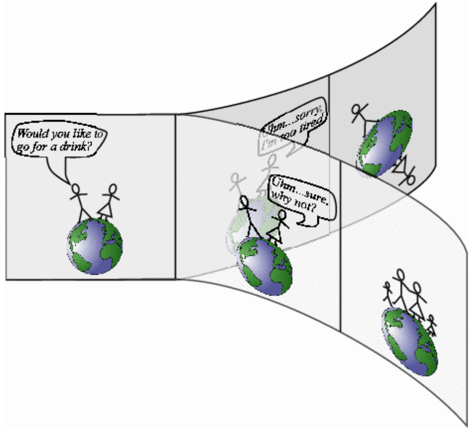
The ordinary-particle picture **works***

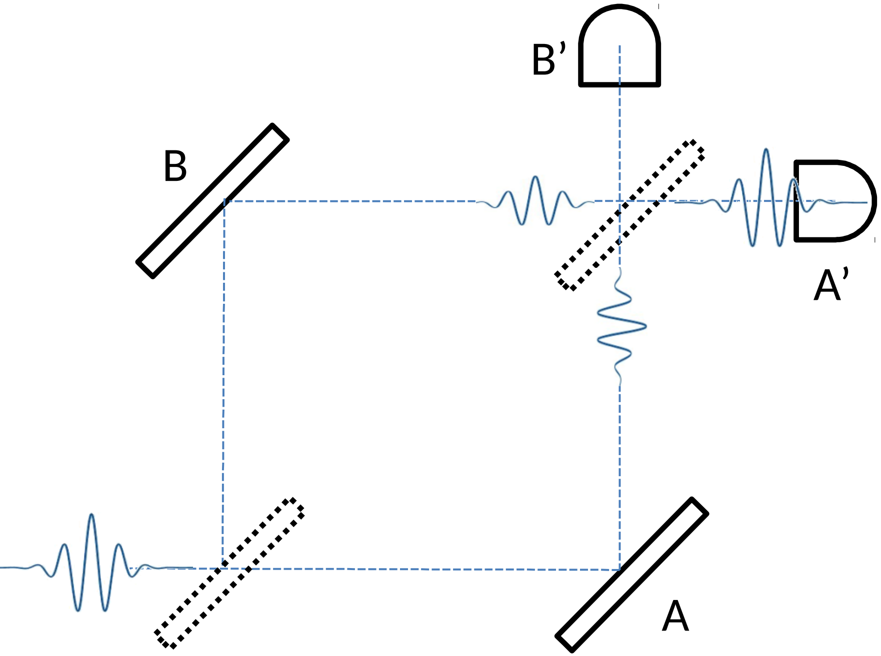
The ordinary-wave picture **fails**





<u>However</u>: We **can** think in terms of waves if we adopt the **many-worlds interpretation** of quantum mechanics. *No mysterious wavefunction collapse*, and *no God playing with dice*.



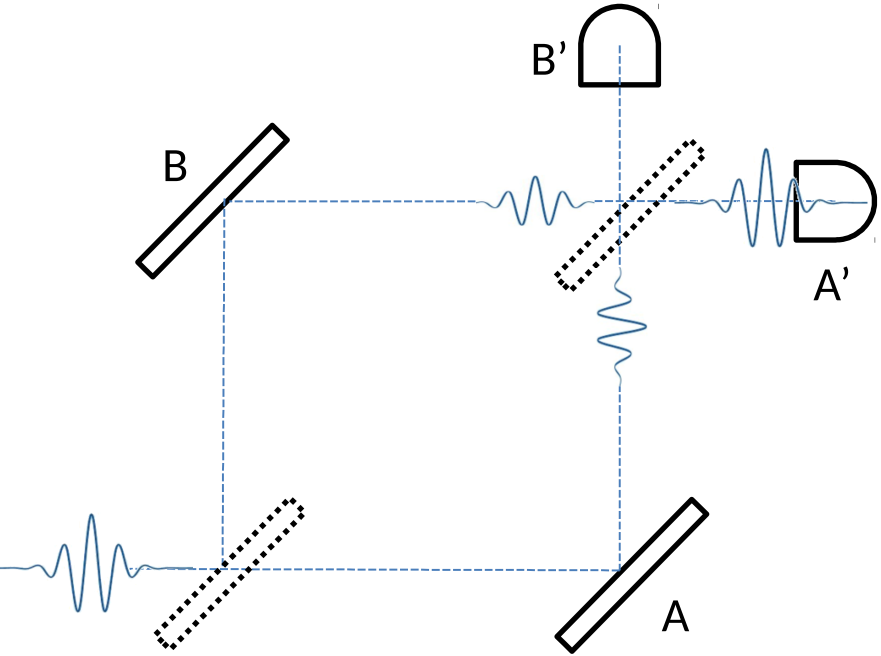


To explain:

100% probability for A'
0% probability for B'

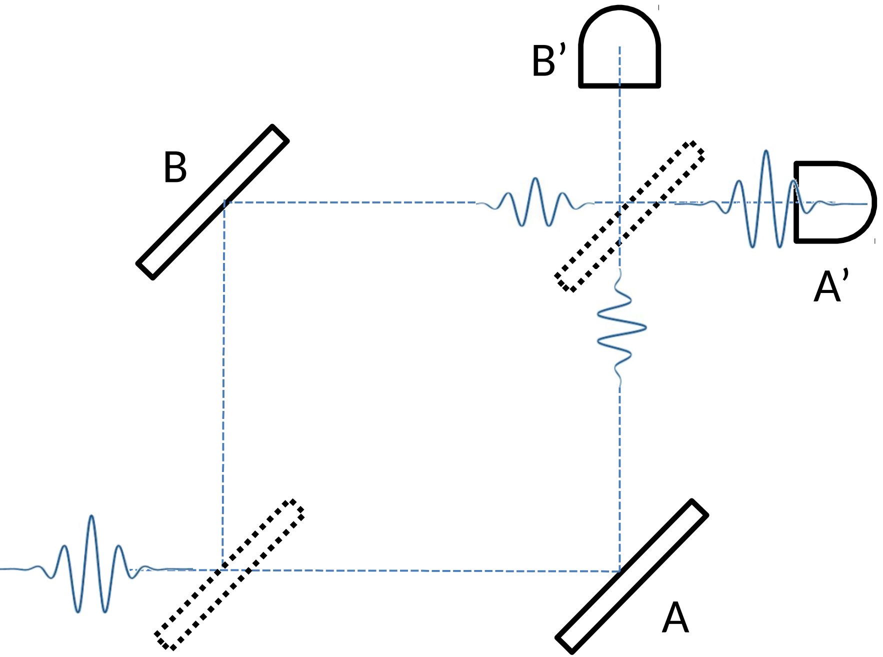
The ordinary-wave picture **works**

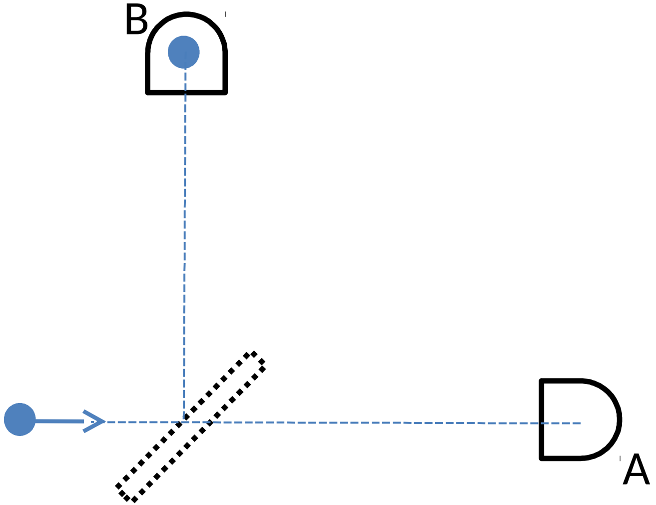
The ordinary-particle picture **fails**



<u>However</u>: We **can** think in terms of particles if we accept that, like a non-localized wave, one particle can '**be in two (or more) places at once**', e.g., at A *and* B, i.e., 'exist in two (or more) paths at once'.

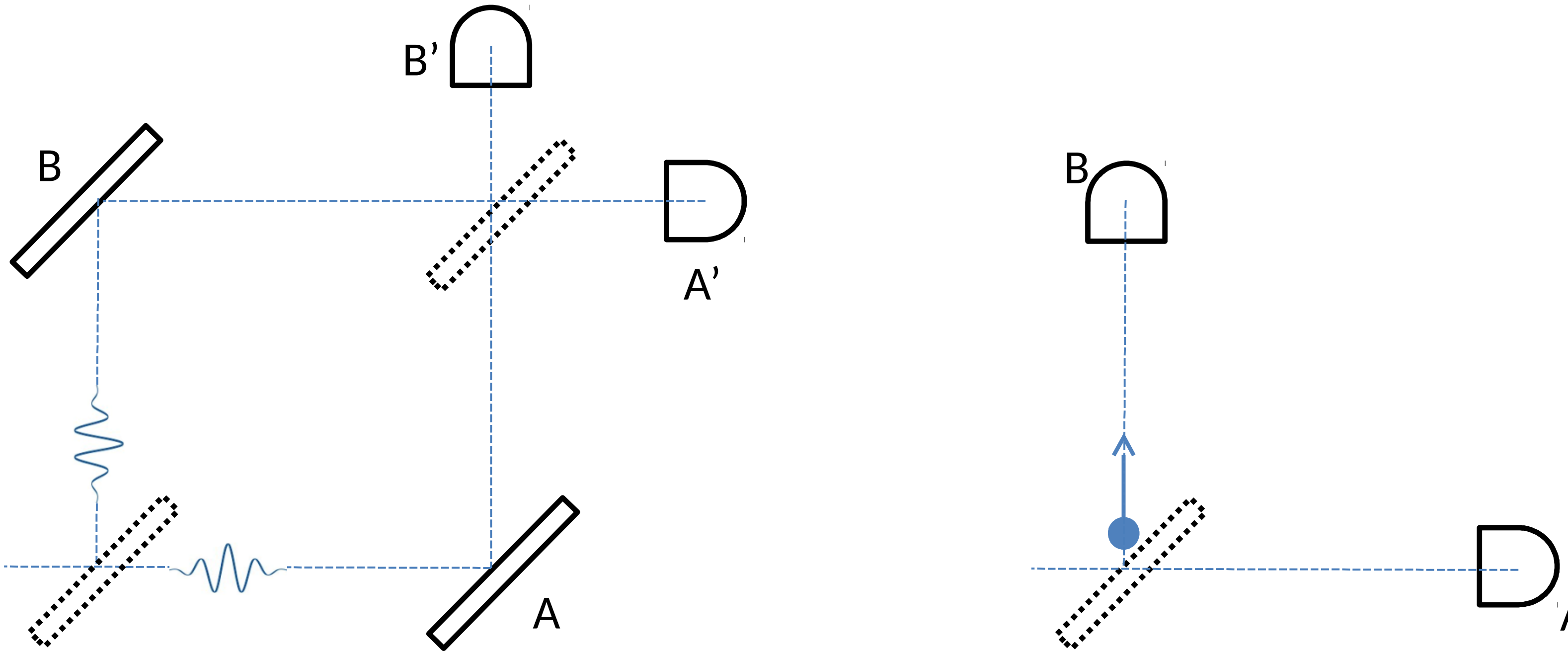
More correctly, the particle can have an "**indefinite position**": at any instant of time it's not definitely here, **or** there. Just "**potentially**" here **and** there *at the same time* (ready for the possibility that A and B replace their mirrors with detectors)



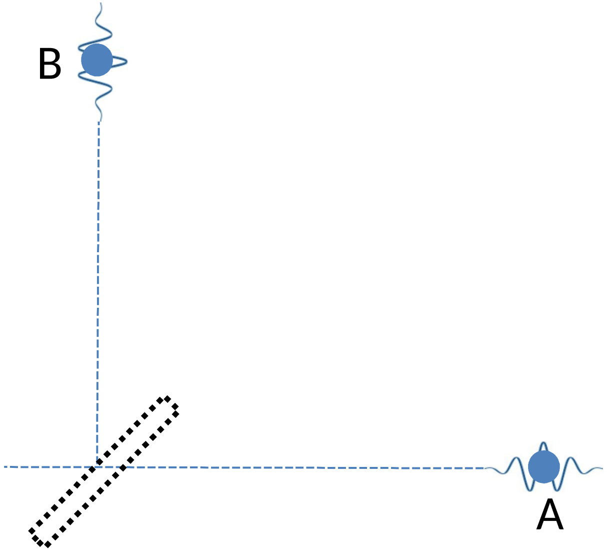


Ordinary-wave picture **works**
Ordinary-particle picture **fails**

Ordinary-particle picture **works**
Ordinary-wave picture **fails**



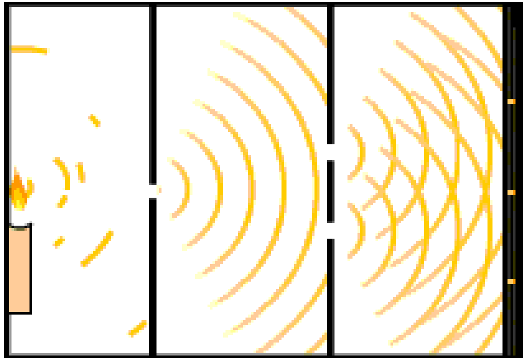
Question: After leaving the first beam splitter, how does light 'know' to behave like a wave or like a particle? How could it have '**foresight**' of the experiment it will next encounter?

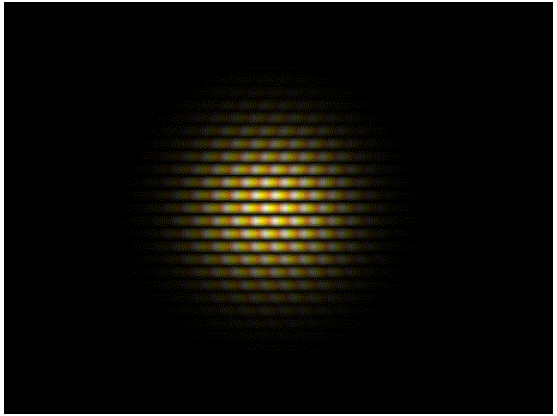


The **alternative** to foresight is for the very nature of light to be such that it is prepared for all eventualities by being able to exhibit **both** wave and particle properties: "**wave-particle duality**".

The **wave** property is needed to explain the **interference** of the split photon wave packet *with itself* (first experiment); the **particle** property is needed to explain the **whole** photon arriving at one **or** the other detector (second experiment).

Einstein: "We are faced with a new kind of difficulty. We have two contradictory pictures of reality; separately neither of them fully explains the phenomena of light, but together they do."



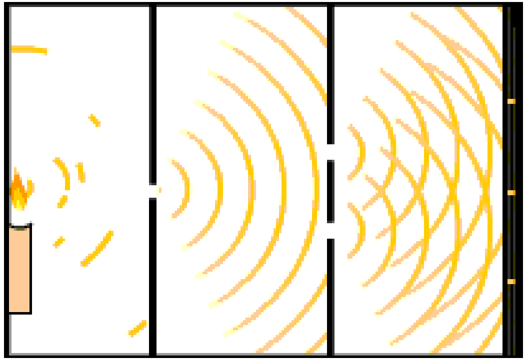


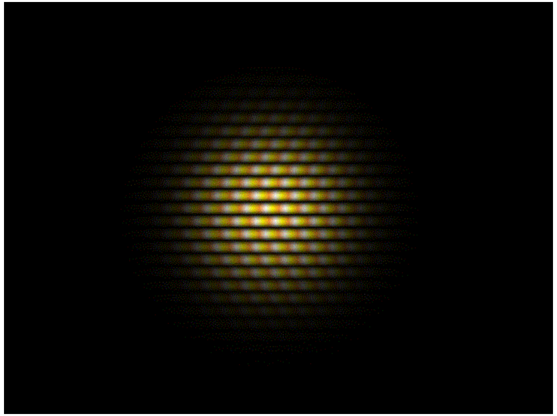
So what?

All entities in nature exhibit this strange **wave-particle duality**: photons, electrons, atoms, large molecules, etc. (Improved technology → larger and larger objects; limited by “decoherence.”)

They can all be “***in two places at once***,” or be made to “***interfere with themselves***.”

At a fundamental level, there are **no classical particles** (e.g., electron like a tiny baseball) and **no classical waves** (e.g., light as electromagnetic wave), only these strange **quantum particles** that exhibit **both** properties.

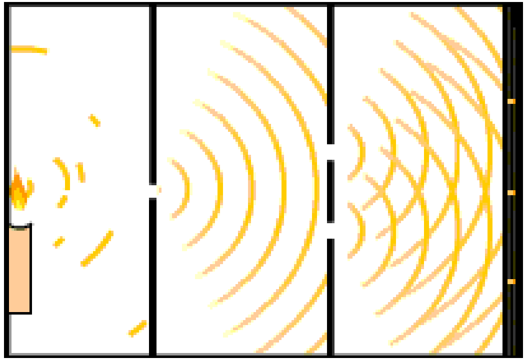


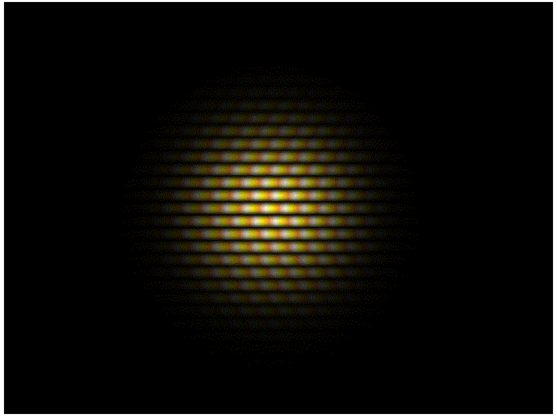


The **quantum nature** of reality represents one of the most **profound unifications** of all.

Nature is somehow able to combine, **without logical contradiction**, two **diametrically opposed properties** (particle = local; wave = non-local) into a **single entity**.

No one saw this coming!





Mathematically, wave-particle duality is expressed by the **de Broglie relation** (Louis de Broglie, 1924; so weird, Einstein was called in as his external thesis examiner…):

$$\lambda\, p = h$$

where λ = **wavelength** (the wave property of the entity) and p = **momentum** (the particle property of the entity) .

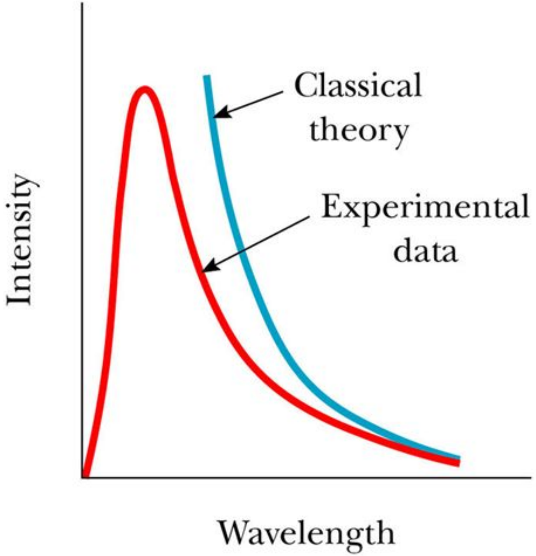
A particle with momentum p behaves like a wave with wavelength $\lambda = h/p$ (e.g., it can bend around corners).

A wave with wavelength λ behaves like a shower of particles with momentum $p = h/\lambda$ (e.g., light = photons)

So what?

This wave-particle duality at the **heart of reality** is essential to how our universe works

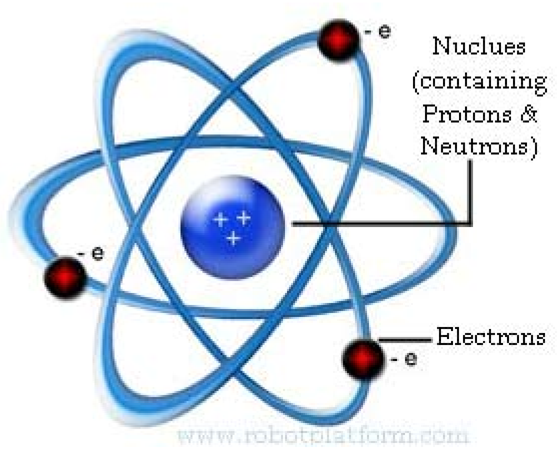
Example: **The Ultraviolet Catastrophe**

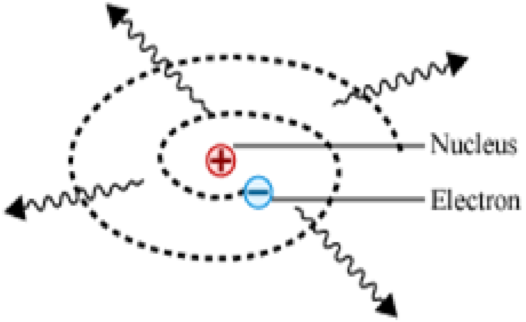


In a **non-quantum** world, these people would be vaporized by ultra intense UV, X-rays and gamma rays from their campfire…

This huge discrepancy (in **thermodynamics**) between reality, and our understanding of reality, was resolved by **Max Planck** in 1900, and was the first step towards unravelling the quantum nature of reality.

Example: **The Atomic Catastrophe**



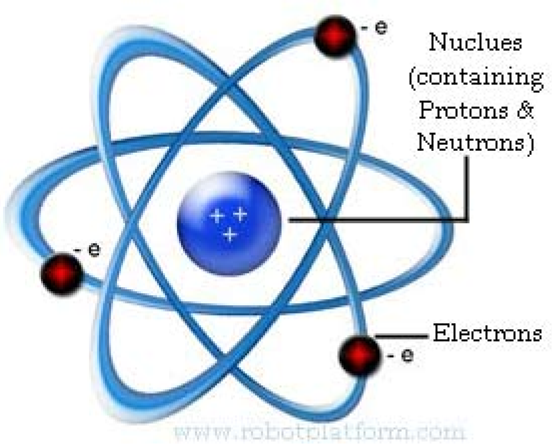


In a **non-quantum** world, electrons would orbit the nucleus like planets orbit the Sun.

But, like electrons **accelerating** in your cell phone antenna, such **accelerating** electrons in the atom would **radiate electromagnetic waves** (light)…

…and these waves would **carry energy away**, making the electron **spiral in to the nucleus**.

Example: **The Atomic Catastrophe**

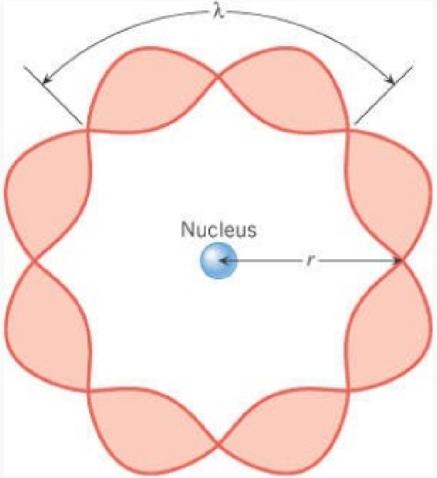


In a **non-quantum** world, electrons would orbit the nucleus like planets orbit the Sun.

In about a **trillionth** of a second, all of the atoms in your body would **collapse** (electrons spiral into the nucleus), releasing a **blinding flash** of light with the intensity of an **atomic bomb**.

Example: **The Atomic Catastrophe**

De Broglie Explanation



$$2\pi r = n\lambda \quad n = 1, 2, 3, \ldots$$

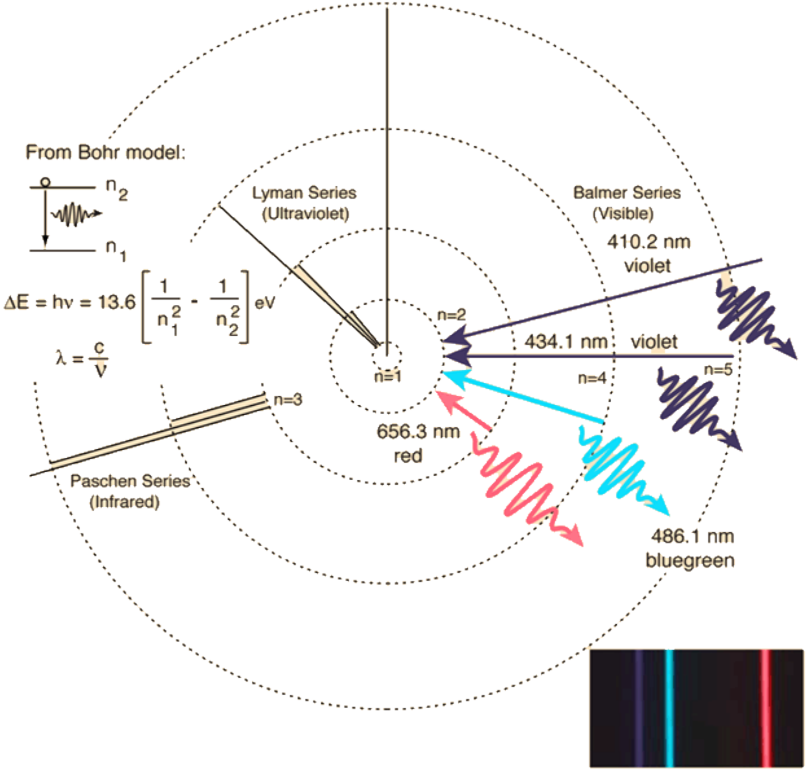
De Broglie suggested standing particle waves as an explanation for Bohr's angular momentum assumption.

What **allows atoms to exist** in our universe is the **quantum behaviour** of the electron:

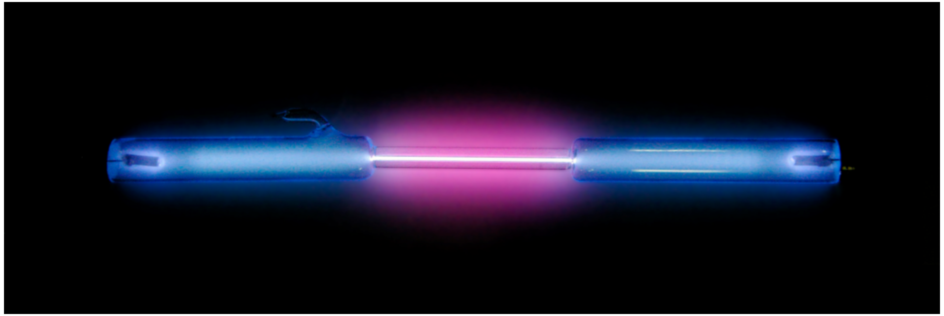
If the electron has momentum p in a circular orbit, it **behaves like a wave** with wavelength $\lambda = h/p$.

In order for this to make sense, an **integer number** of wavelengths must fit around the circular orbit (e.g., 4 wave-lengths in the picture).

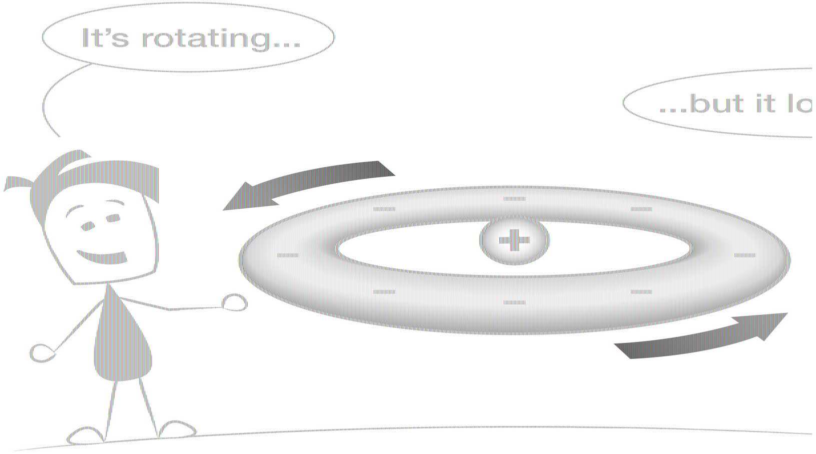
Example: **The Atomic Catastrophe**



This explains the **discrete spectral lines** of light emitted by excited atoms.



Example: **The Atomic Catastrophe**

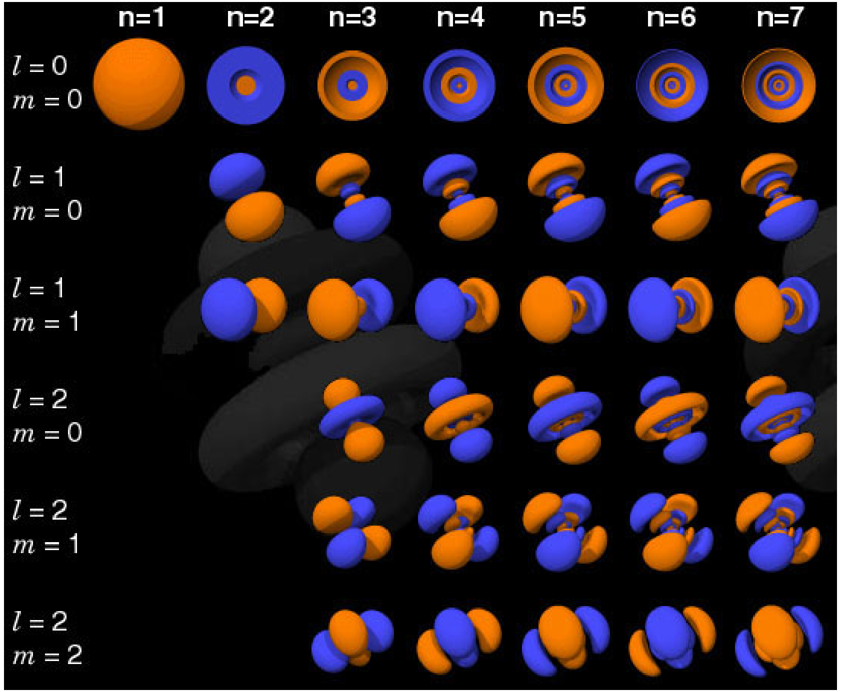


But more importantly, it also explains the **stability** of atoms: *why the orbiting electron does not radiate electromagnetic waves*.

The electron behaves as if it is in many places at once, ***effectively*** (but not literally) spreading it into a **uniform, rotating ring of charge**.

Such a rotating ring looks **static**: it will create a magnetic field, but **not electromagnetic waves**.

Example: **The Atomic Catastrophe**

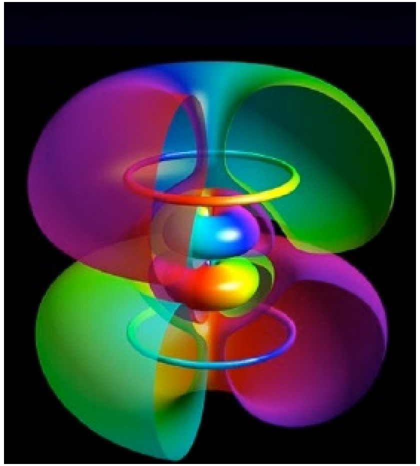


In a real atom, each electron behaves as if it is in **many places at once**.

In can also behave as if it is **moving in different directions at once**!

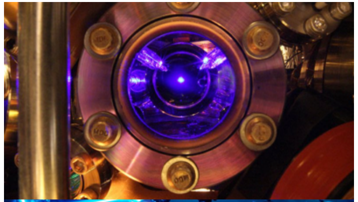
See falstad simulation.

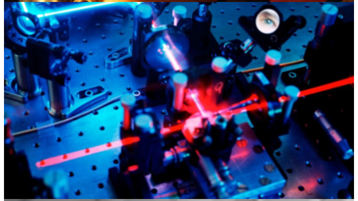
So quantum mechanics underpins all of **Chemistry ▭ LIFE**, etc…

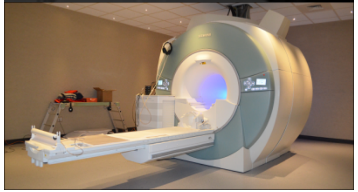


Why We Need Quantum Mechanics

Applying our understanding of the quantum nature of reality has also been the **single greatest driver** of **technological revolution** the world has ever seen.







Ultra-precise **atomic clocks** that synchronize our technological world (heart of the GPS, as well as many high precision science experiments).

Lasers (everything from industry and health to carrying most of the world's internet traffic; plus creating uncrackable crypto codes).

Semiconductor-based electronics (the entire computer industry including computing and memory devices, the whole cell phone industry, solar cells, image sensors in digital cameras…*everywhere*).

Magnetic resonance and many other medical imaging technologies.

Etc…

Why We Need Quantum Mechanics

Applying our understanding of the quantum nature of reality has also been the **single greatest driver** of **technological revolution** the world has ever seen.

An estimated **one third** of the total US GNP is based on quantum inventions. *And it has only just begun*.

Potential future applications in quantum **computing**, quantum **artificial intelligence**, quantum **communications**, quantum **teleportation**, etc., promise technological advancements undreamed of even a few years ago.

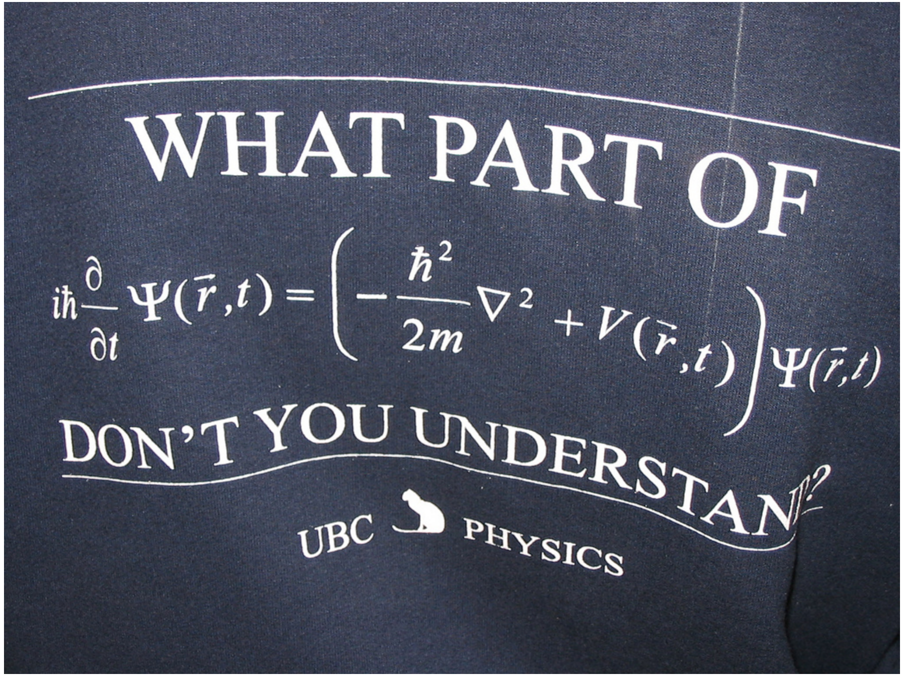
There is no doubt that "**the future is quantum**".

So What?

What does it tell us about the ultimate nature of reality?

Erwin Schrödinger invented the **wave equation** that the quantum wavefunction must satisfy.

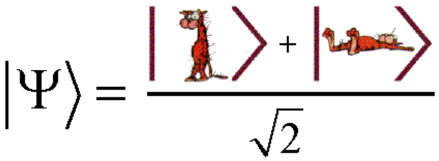
It is the "master key" for much of modern physics.



Schrödinger’s Cat

He was also the first to realize some of the **most bizarre implications** of quantum mechanics.

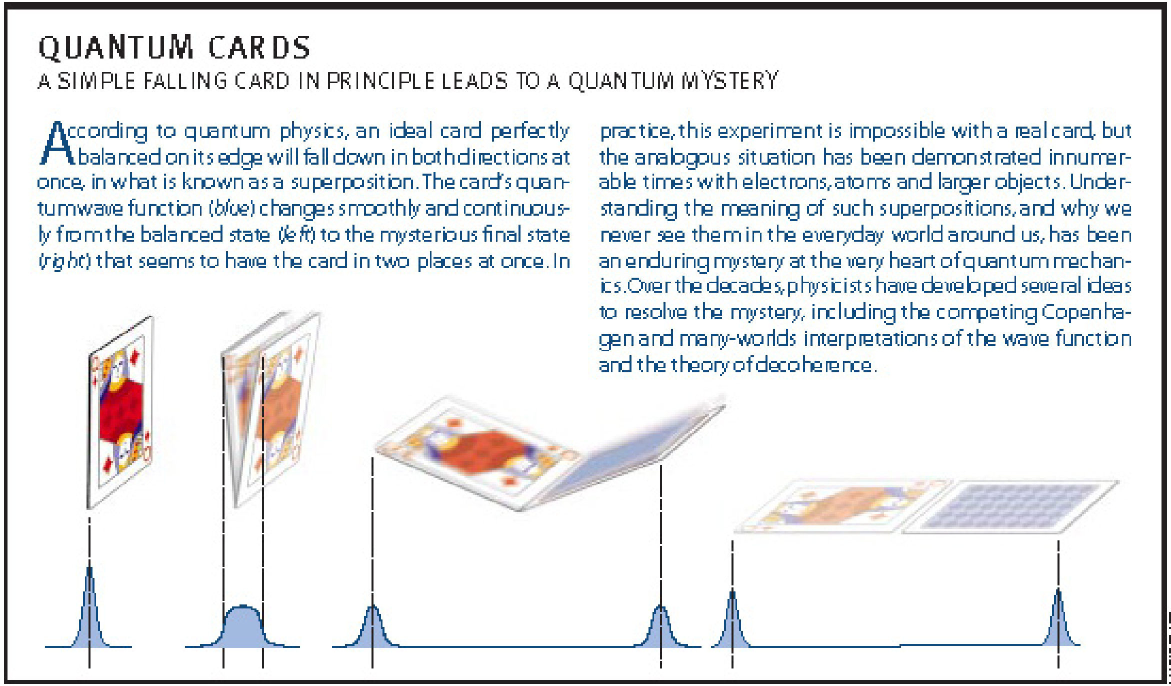
If **microscopic** things can be in a **quantum superposition** (e.g., in two places at once, or moving in two directions at once, or radioactively decayed/not decayed), *so can **macroscopic** things*.



This cat is in a *quantum superposition of being dead and alive at the same time*.

What could this possibly mean?

Quantum Card (from Scientific American, Feb 2001: Max Tegmark & John Archibald Wheeler)



QUANTUM CARDS

A SIMPLE FALLING CARD IN PRINCIPLE LEADS TO A QUANTUM MYSTERY

According to quantum physics, an ideal card perfectly balanced on its edge will fall down in both directions at once, in what is known as a superposition. The card's quantum wave function (*blue*) changes smoothly and continuously from the balanced state (*left*) to the mysterious final state (*right*) that seems to have the card in two places at once. In practice, this experiment is impossible with a real card, but the analogous situation has been demonstrated innumerable times with electrons, atoms and larger objects. Understanding the meaning of such superpositions, and why we never see them in the everyday world around us, has been an enduring mystery at the very heart of quantum mechanics. Over the decades, physicists have developed several ideas to resolve the mystery, including the competing Copenhagen and many-worlds interpretations of the wave function and the theory of decoherence.

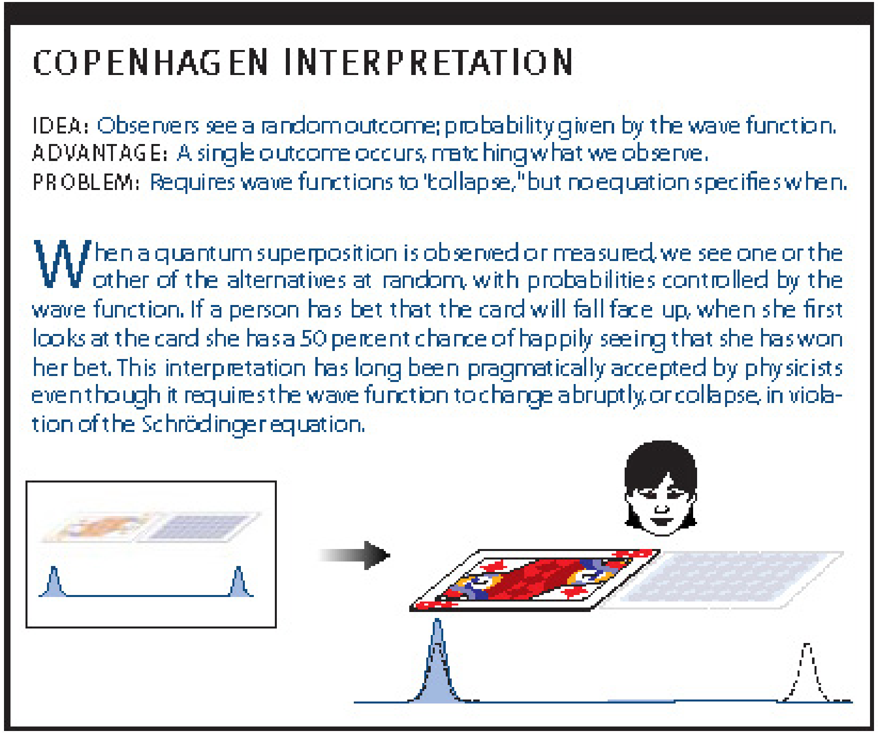
LAURIE GRACE

In a **non-quantum** world, the card could be perfectly balanced and **never fall**.

Schrödinger equation it **must fall** in a few seconds, in **both directions**, in a **quantum superposition** of face up (left) and face down (right): a state of **“indefinite” position**.

We observe that it falls, but in **one direction only**, seemingly at **random**. Why the <u>**contradiction**</u>?

Quantum Card (from Scientific American, Feb 2001: Max Tegmark & John Archibald Wheeler)

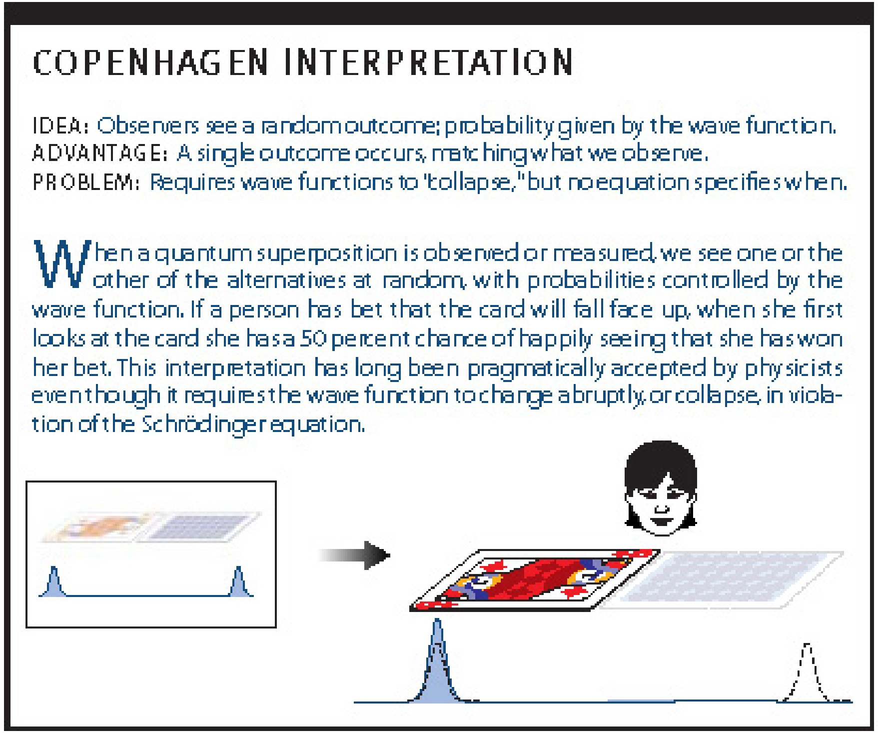


Observations (or measurements) are **special**.

When we are **not observing**, the card’s wave-function obeys the **deterministic** Schrödinger equation, spreading into the 50/50 right/left superposition…a state of **indefinite** position.

When we **observe** the card, its wavefunction **stops** obeying the Schrödinger equation and suffers a mysterious, **in-deterministic** “collapse” to one side or the other, with **probability** determined by the original wavefunction. The card ends up in a state of **definite** position.

Quantum Card (from Scientific American, Feb 2001: Max Tegmark & John Archibald Wheeler)



COPENHAGEN INTERPRETATION

IDEA: Observers see a random outcome; probability given by the wave function.
ADVANTAGE: A single outcome occurs, matching what we observe.
PROBLEM: Requires wave functions to "collapse," but no equation specifies when.

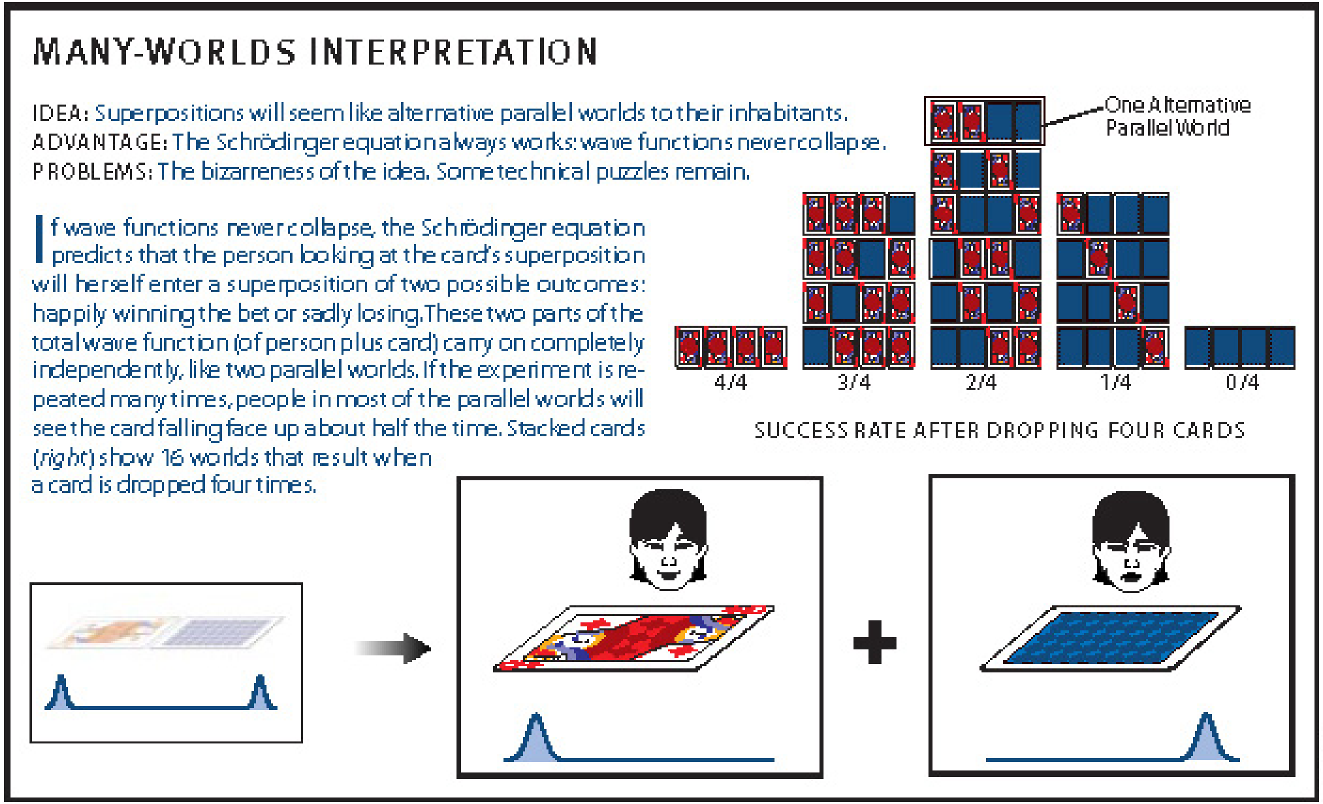
When a quantum superposition is observed or measured, we see one or the other of the alternatives at random, with probabilities controlled by the wave function. If a person has bet that the card will fall face up, when she first looks at the card she has a 50 percent chance of happily seeing that she has won her bet. This interpretation has long been pragmatically accepted by physicists even though it requires the wave function to change abruptly, or collapse, in violation of the Schrödinger equation.

While this **pragmatic** approach **<u>worked</u>** (quantum mechanics was quickly discovered to be the most *powerful*, *accurate and reliable description of reality the world had ever seen*), it was "ontologically" **highly unsatisfactory**:

What's so special about "**observation**"? Isn't it a physical process like any other? Why does it **not obey** the Schrödinger equation? Exactly **when** and **how** does "wavefunction collapse" occur?

Why is nature **deterministic** when we're "**not looking**," and **probabilistic** when we "**look**"?

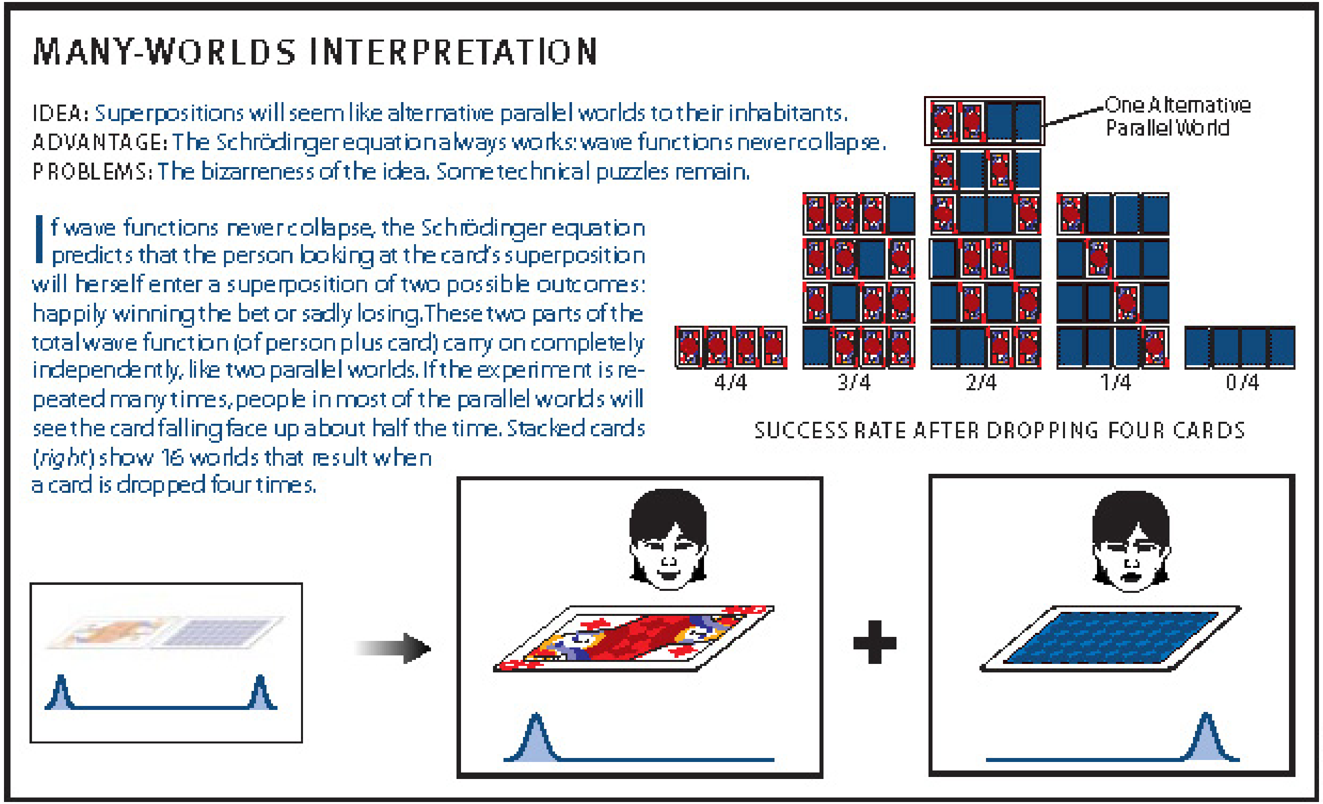
Quantum Card (from Scientific American, Feb 2001: Max Tegmark & John Archibald Wheeler)



1950s: Hugh Everett III: Observations **not** special.

The card really **does** fall both ways. The observer is **part** of the quantum world, and **observing** the cards **in superposition** puts the observer *herself* into a quantum **superposition** alternate branches of reality: **many-worlds**.

Quantum Card (from Scientific American, Feb 2001: Max Tegmark & John Archibald Wheeler)



1950s: Hugh Everett III:
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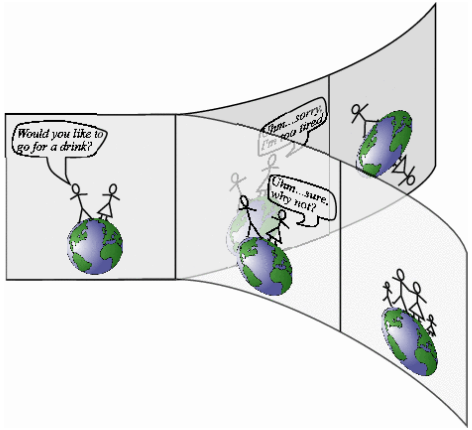
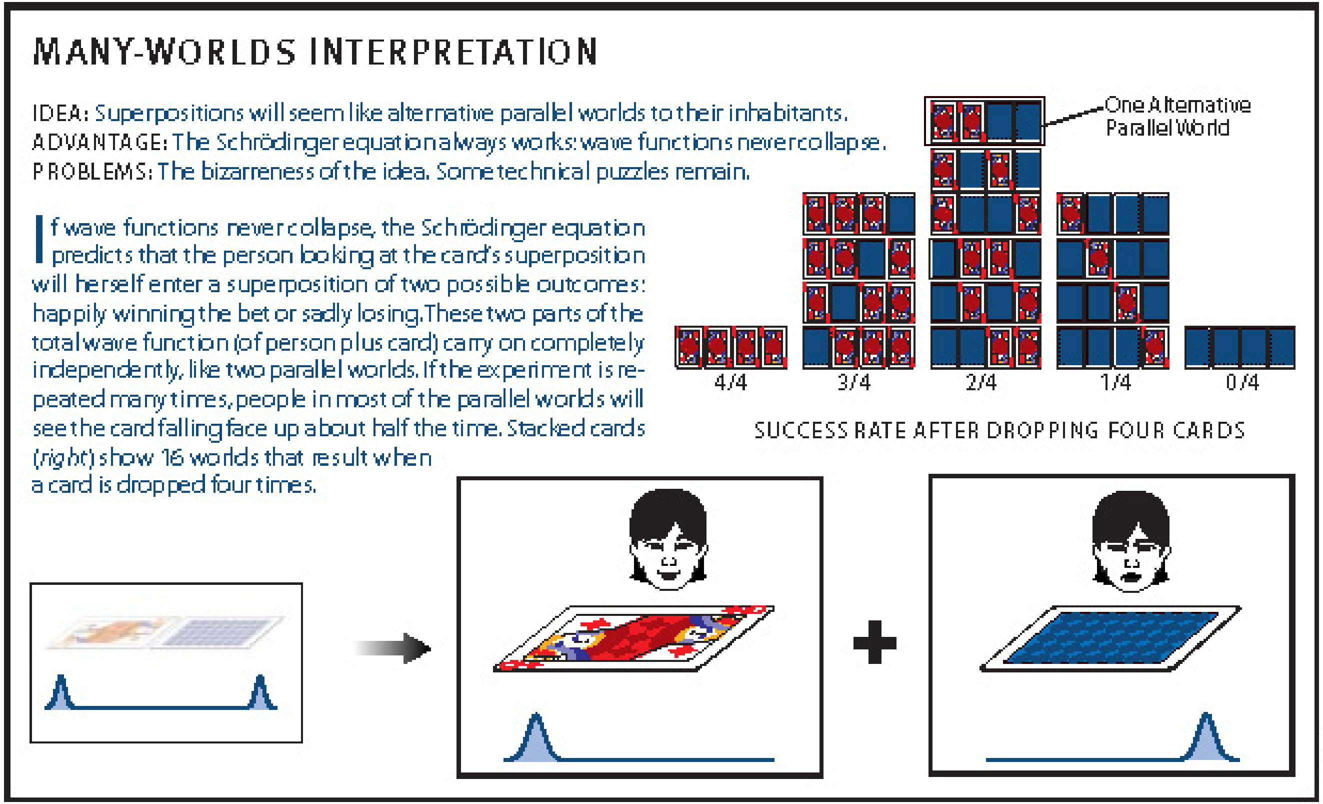


Quantum Card (from Scientific American, Feb 2001: Max Tegmark & John Archibald Wheeler)



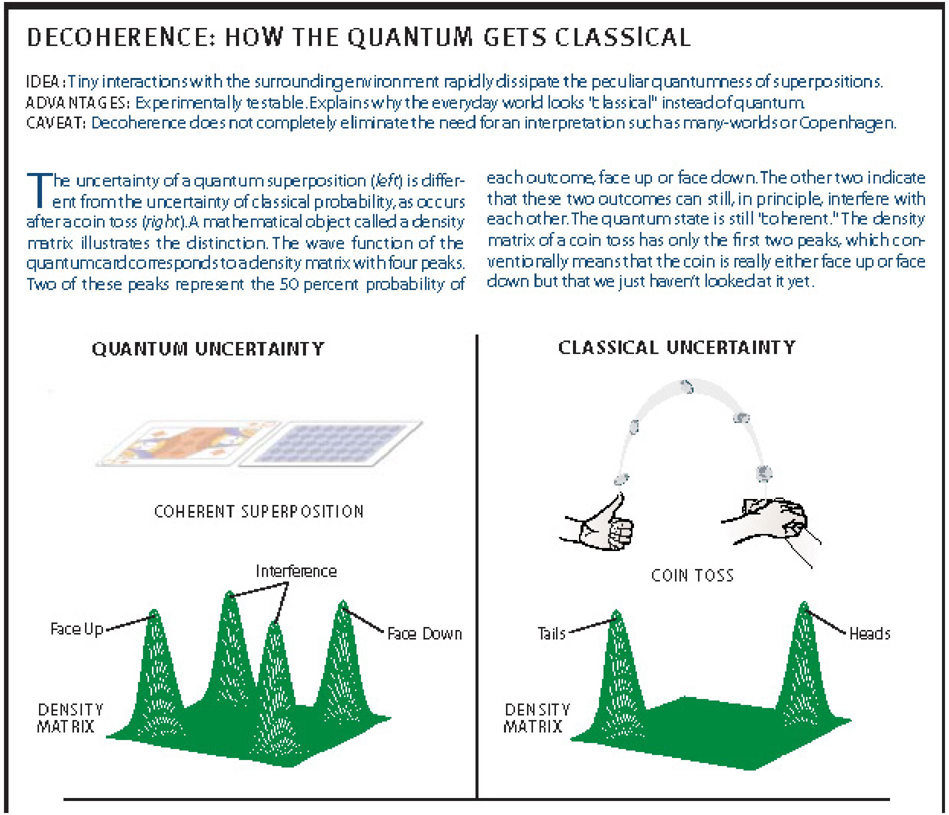
1950s: Hugh Everett III: Observations **not** special.

The **whole universe** is described by a **giant wavefunction** that obeys the **deterministic** Schrödinger equation.

No mysterious wave-function collapse; no God playing dice…

…at the expense of a **stu-pendous excess** of

Quantum Card (from Scientific American, Feb 2001: Max Tegmark & John Archibald Wheeler)

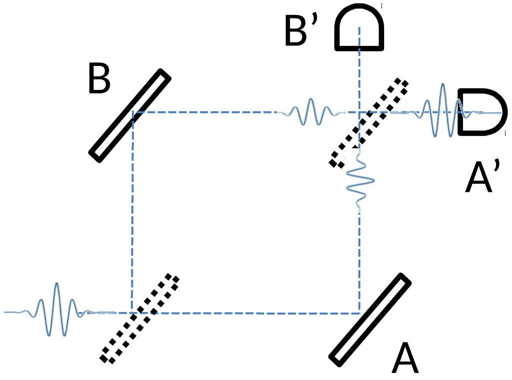

DECOHERENCE: HOW THE QUANTUM GETS CLASSICAL

IDEA: Tiny interactions with the surrounding environment rapidly dissipate the peculiar quantumness of superpositions.
ADVANTAGES: Experimentally testable. Explains why the everyday world looks "classical" instead of quantum.
CAVEAT: Decoherence does not completely eliminate the need for an interpretation such as many-worlds or Copenhagen.

The uncertainty of a quantum superposition (*left*) is different from the uncertainty of classical probability, as occurs after a coin toss (*right*). A mathematical object called a density matrix illustrates the distinction. The wave function of the quantum card corresponds to a density matrix with four peaks. Two of these peaks represent the 50 percent probability of each outcome, face up or face down. The other two indicate that these two outcomes can still, in principle, interfere with each other. The quantum state is still "coherent." The density matrix of a coin toss has only the first two peaks, which conventionally means that the coin is really either face up or face down but that we just haven't looked at it yet.

A quantum superposition contains **extra information** ("interference") beyond just the 50/50 classical uncertainty of face up/down. This makes the wavefunction "**coherent**."

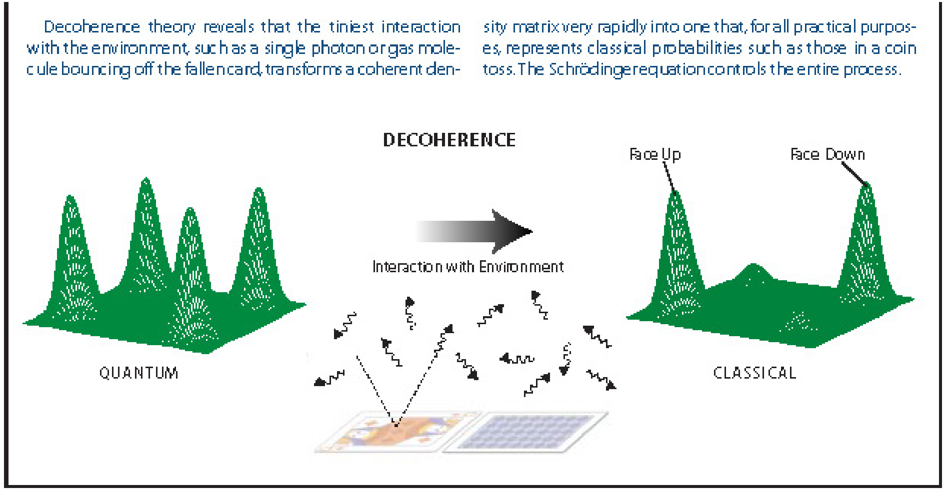
E.g., this **extra info** in the wavefunction is what is needed to get 100% A', 0% B'.



Decoherence

Quantum Card (from Scientific American, Feb 2001: Max Tegmark & John Archibald Wheeler)

Coherent superpositions are very delicate, and persist only if the system is **perfectly isolated.** **Tiny interactions with the environment**, e.g., an air molecule or thermal photon, can “find out” (“observe”) what the card is doing. Like a friend who has observed the card (and “collapsed the wavefunction”), but not told you what she saw $\Rightarrow$ 50/50 classical uncertainty of face up/down. The **quantum weirdness** (extra info) has “leaked into” the environment: called “**decoherence**.”



The environment (or even macroscopic object interacting with itself) acts as an “observer,” making the quantum world look classical: we don’t see cats that are alive **and** dead.

Decohence is **extremely fast**, and controlled entirely by the Schrödinger equation. It’s not quite **collapse**, but “looks and smells” like it…