A brief introduction to Quantum Physics and some of its Startling Implications

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Talk Outline

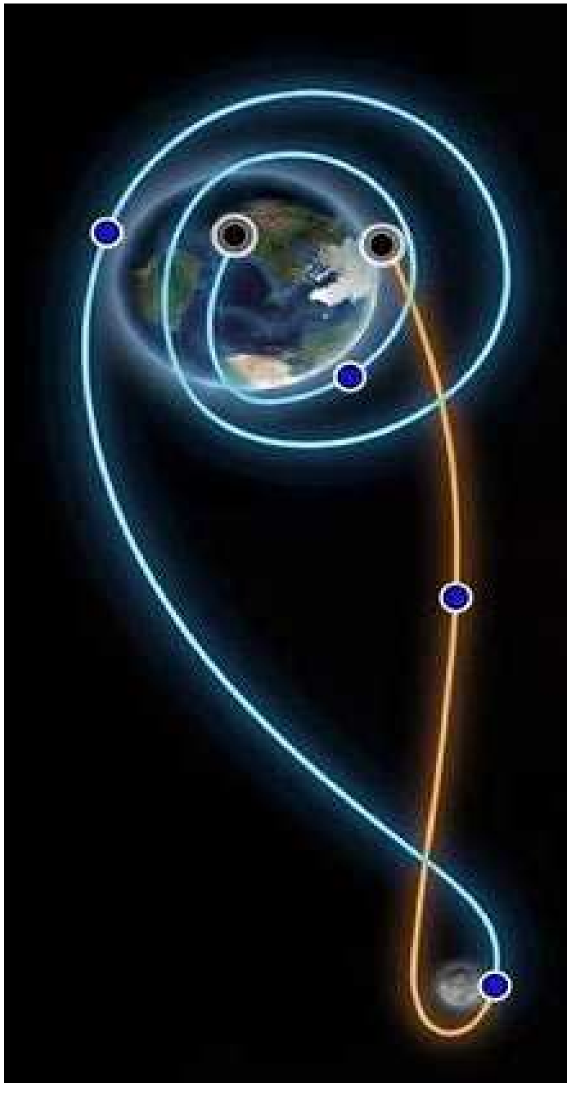
- **Introduction to the Quantum Mechanical Worldview**
  - Comparison of the Domains and Philosophical Implications of Quantum versus Classical Physics
- **The First Weirdness: Wave – Particle Duality**
  - Neither waves nor particles, but a non-intuitive mixture of both at the same time
- **How Probabilities work in Quantum Mechanics**
  - Superposition of Quantum States
  - Quantum Tunneling
- **The Second Weirdness: Quantum “Reality”**
  - What “exists” Before and After you do a Quantum Measurement
  - Schrődinger’s Cat
  - Quantum Computing: Qubit Superposition
- **The Third Weirdness: Quantum Entanglement**
  - Quantum Particles: Indistinguishability and Spin
  - Einstein-Podolsky-Rosen Experiment
  - Quantum Encryption: Exchange of Entangled Photon Pairs

The Quantum Mechanical Worldview

The Domain of Classical Physics

Newtonian physics remains applicable to the large-scale world, but it does not work in the subatomic domain

- *Newton's First Law:* **A body in motion remains in motion**
  - We can use Newton's laws of motion to predict the future path of a moving object provided we know certain things about it initially.
  - The more initial information we know, the more accurate our predictions will be.
- The remarkable accuracy of the Artemis II trajectory demonstrates the continued validity of Classical mechanics and the skill of the NASA scientists



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The Domain of Quantum Mechanics

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- Every particle or system of particles *can* be defined in Quantum Mechanical terms, and therefore have wave-like properties
- **Quantum (de Broglie) wavelength of an object: $\lambda = h/p$**
  - p = momentum, $h = 6.62\times10^{-34}\ \mathrm{m^2\cdot kg/s}$ Planck's constant
- **Typical "classical" objects:**
  - masses ~ kg; velocities ~ m/s $\rightarrow$ momentum $p \approx 1$ kg·m/s
  - $\lambda \approx 10^{-34}$ meters (too small to matter in macro environment!!)
- **Typical "quantum" objects:**
  - electron (10^{-30} kg) at thermal velocity (10^5 m/s) $\rightarrow \lambda \approx 10^{-8}$ m
  - so λ is 100 times larger than an atom: very relevant to an electron!

What is Quantum Mechanics?

- **Quantum Mechanics forced itself upon the scientific scene at the beginning of the 20th century**
  - No convention of physicists noted to start a new branch of physics called "Quantum Mechanics"
  - Physicists were confronted with *shocking* scientific data that were at odds with the conventional wisdom
  - No one had any choice in the matter, except what to call it
- A **Quantum** is a small quantity of something
- **Mechanics** is the study of motion
- **Quantum theory** says that nature comes in small pieces (quanta) and **Quantum Mechanics** is the study of this phenomenon
- **Quantum Mechanics does not replace Classical (Newtonian) mechanics, but includes it**

Is the Universe Deterministic?

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- **The ability to predict the future based on the knowledge of the present and the laws of motion is very powerful, but it comes with an inherent dispiriting implication**
- If the laws of mature determine the future of an event, then, given enough information, we can also use this information to predict the trajectories of objects in the very distant past
- If we are to accept the mechanistic determination of Newtonian physics, if the universe really is a great machine, then from the moment that the universe was created and set into motion, everything that was to happen in it was already determined
- **Quantum Mechanics forces us to break from this deterministic view. It is not possible, even in principle, to know enough about the present to make a complete prediction of the future**

Everything is Uncertain on the Quantum Scale

- **Imagine an object moving through space. It has both a position and a momentum we can measure**
  - *Momentum is a combination of how massive an object is, how fast it is moving, and the direction it is moving*
  - Since we can determine both the position and momentum of a classical object at a particular time, it is not very difficult to calculate where it will be at some point in the future
- **In the quantum realm, we CANNOT know both the position AND momentum of a particle with absolute precision**
  - We can know both approximately, but the <u>more</u> we know about one, <u>the less we know about the other</u> (Heisenberg Uncertainty Principle)
  - We can know one of them precisely, but at the cost of knowing NOTHING about the other
- **Because we can only imprecisely predict both the position and momentum of subatomic particles, our prediction of their future movement is greatly restricted**

Quantum Indeterminacy

- **Quantum Mechanics DOES NOT and CANNOT predict specific events**
  - It does, however, predict PROBABILITIES
  - Probabilities are the odds that something is going to happen, or that it is not going to happen
- Quantum Mechanics can predict the probability of a microscopic event with the same precision that Newtonian mechanics can predict the actual occurrence of a macroscopic event
  - Newtonian: *If "A" is the case now, then "B" is going to happen next*
  - Quantum: *If "A" is the case now, then the probability that "B" will happen next is…*
- **We can NEVER know with certainty what will happen to the particle we are observing. All we can know for sure are the probabilities for it to behave in certain ways**

Quantum vs Classical Viewpoints

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- **Newtonian Physics:** the universe is governed by laws that are susceptible to our rational understanding. By applying these laws, we extend our influence over our environment
- **Quantum Physics:** our knowledge of what governs events on the quantum scale is at odds with our daily knowledge
- **Unlike our classical experience, the actions of quantum observed system and observer are <u>not separable</u>**
  - Not only do we influence our reality, but to some degree we actually *create* it
  - Since we can know precisely either the momentum or position of a particle, <u>but not both</u>, we must *choose* which one to determine
  - If we are intent on precisely measuring position → we *see* something that has *well-defined position* (e.g. a particle)
  - Instead, if we decide to precisely measure momentum → we *see* something that is *delocalized* (e.g. a wave)

Summary of Classical vs Quantum

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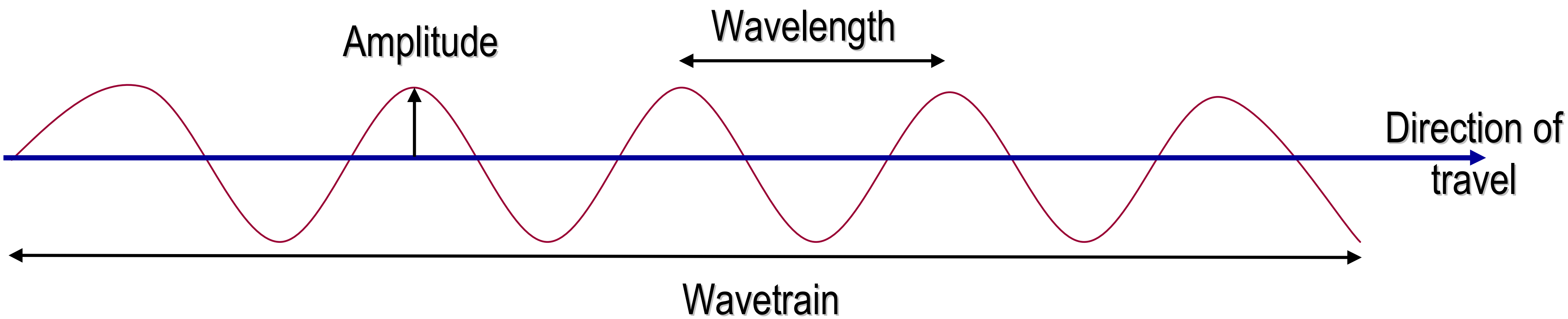
Newtonian Physics	Quantum Physics
You can accurately picture what is going on in the classical world	The quantum realm is far outside our daily experience
Based on ordinary sense perceptions	Based on behavior of subatomic particles and systems that are not directly observable
Describes *things*: individual objects in space and their changes in time	Describes *statistical behavior of systems* (ensembles of particles)
Predicts events	Predicts probabilities of events occurring
Assumes there <u>is</u> an objective reality independent of the observer	<u>Does not</u> assume an objective reality apart from our experience
We <u>can</u> observe something without changing it	We <u>cannot</u> observe something without changing it
Claims to be based on “absolute truth”, i.e. the way that nature really is “behind the scenes”	Claims only to correlate experience correctly

This is Quantum Mechanics. The next question: “How does it work?”

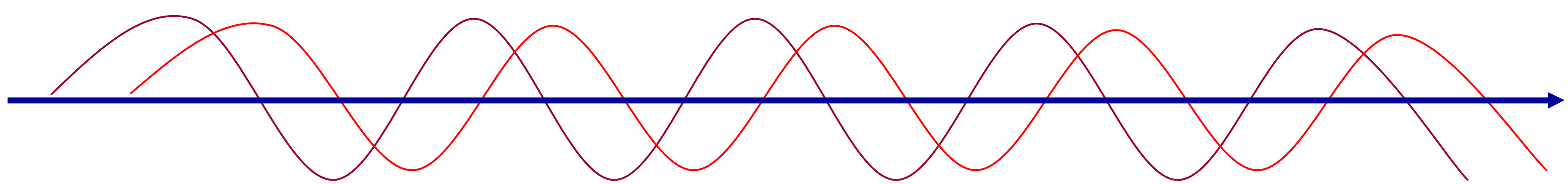
The First Weirdness: Wave – Particle Duality

Wave Mechanics Basics

- **Wavelength:** the distance from one crest of a wave to another
- **Amplitude:** the height of the wave crest
- **Frequency:** how many crests pass a given point in 1 second
- **Wavetrain:** full extent of the crests of the wave



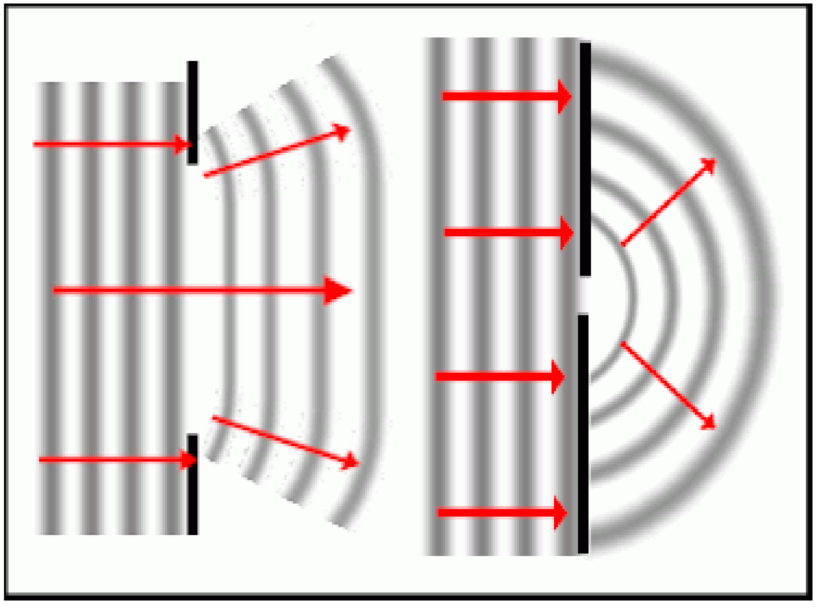
- Waves interfere with each other, they can reinforce each other or cancel each other out if their wavetrains overlap



Wave Diffraction

- Waves can also bend around corners under certain conditions. When this happens it is called diffraction

Large Opening:
- waves entering the mouth of a harbor continue mostly in straight lines
- Occurs if harbor mouth is much larger than wavelength



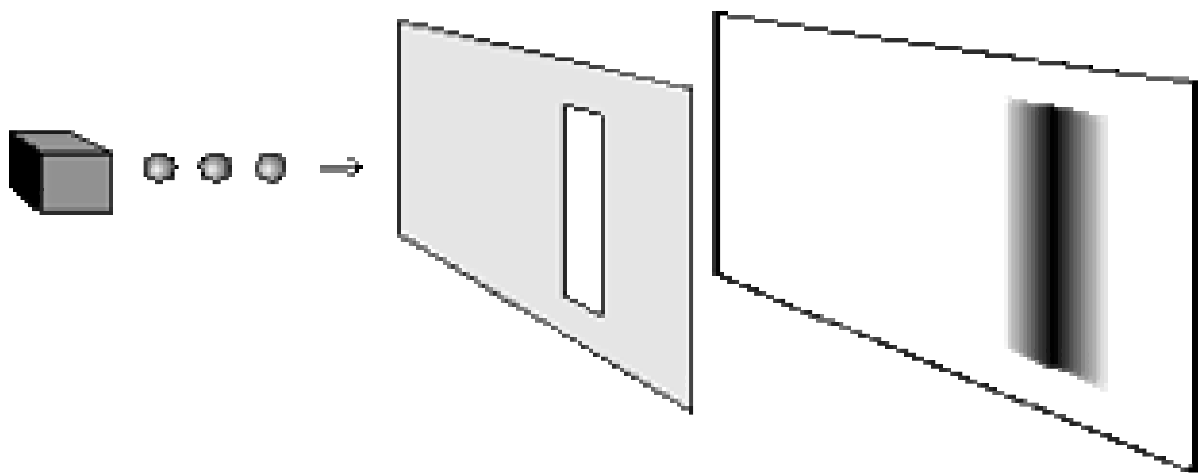
UCSD Physics 10

Small Opening:
- the waves spread in circles if the harbor mouth is comparable to the wavelength

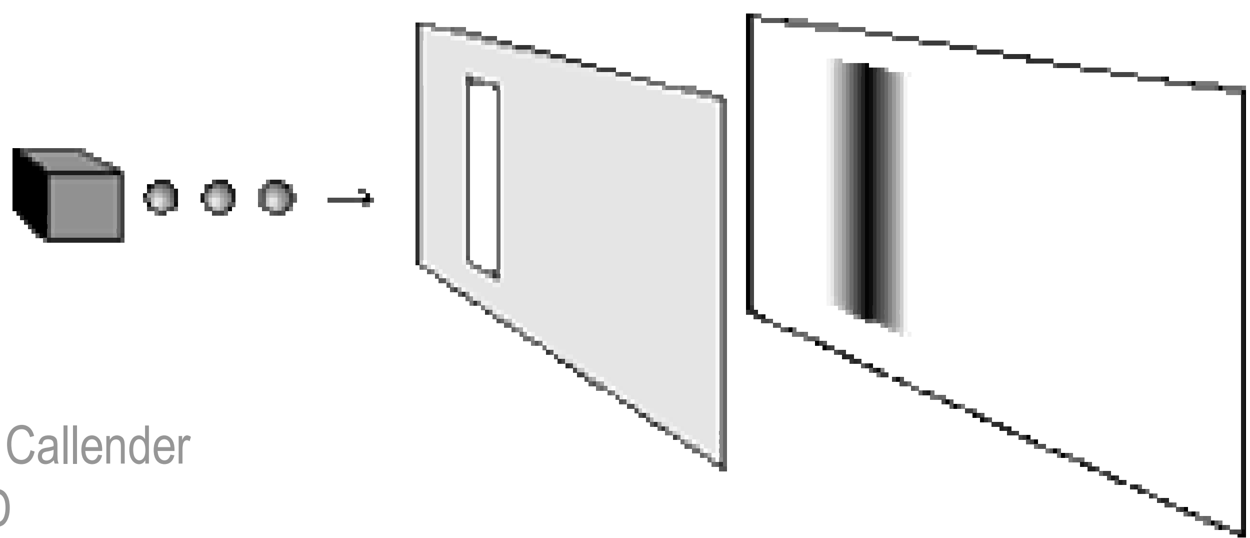
Young's Experiment – 1 Slit at a Time

- In 1803, Thomas Young performed an experiment to settle the nature of whether light is a particle or a wave
- If light is a particle, we expect:

Right Slit Open



Left Slit Open



Craig Callender
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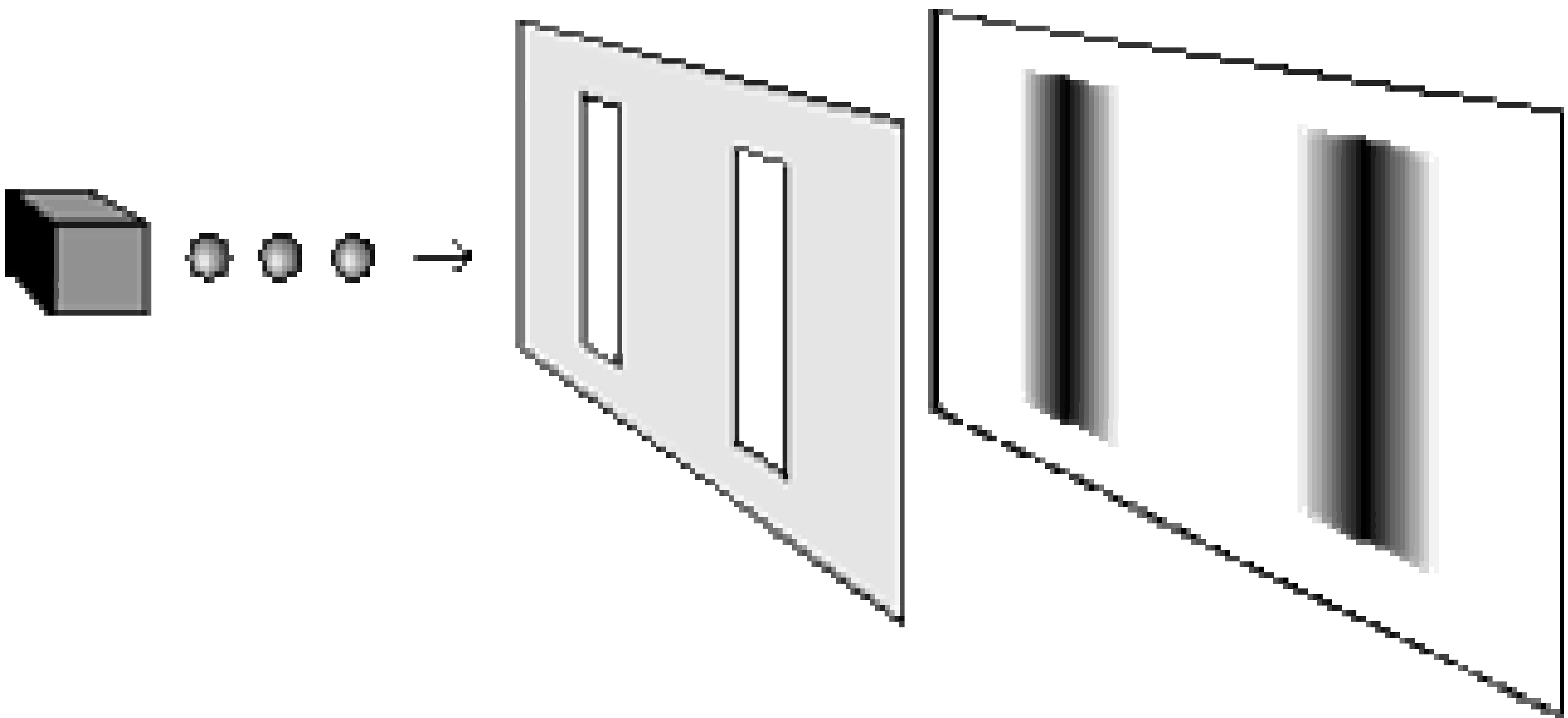
Young's Experiment – 2 Slits Open

If light is a particle, with 2 slits open what you would expect is…



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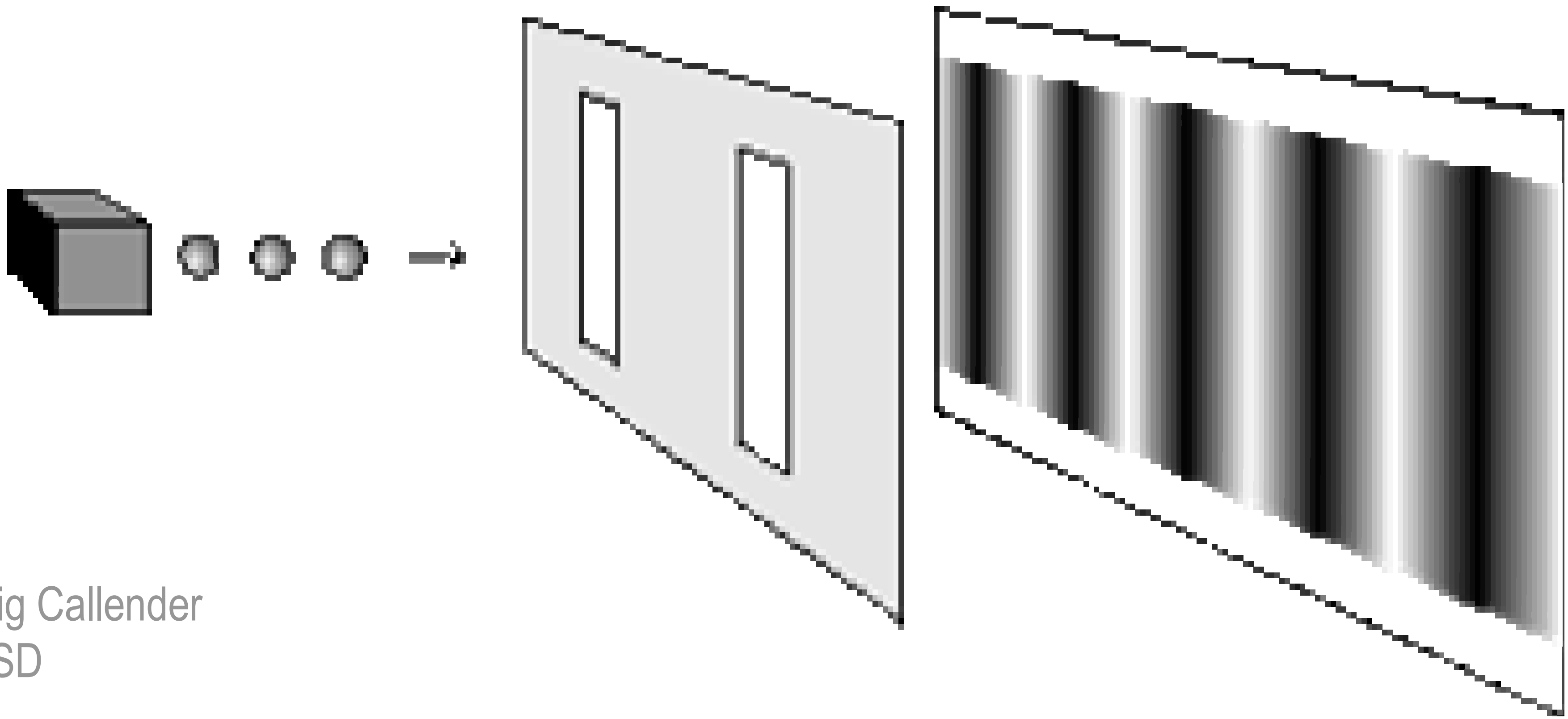
But what actually happens is…



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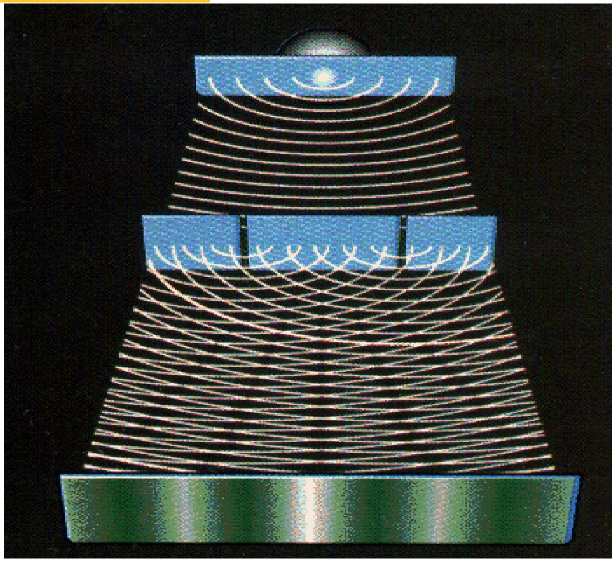
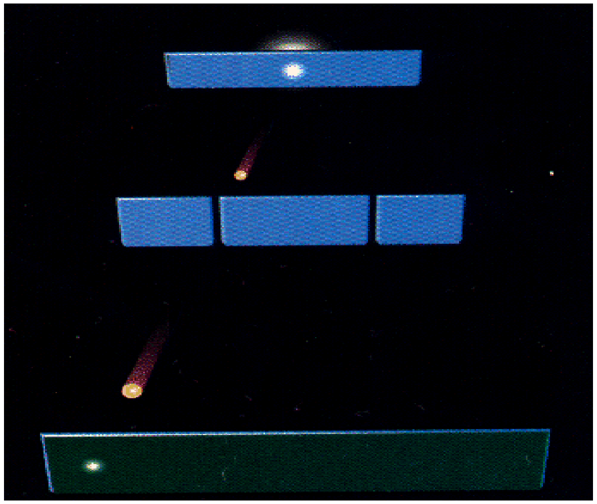
- **The observed pattern is a diffraction pattern, proving that light behaves as a wave**

What about those things called Photons?

- **Fundamental nature of a wave:**
  - Spread out in a wavetrain, not precisely localized
  - Diffracts around corners
  - Spreads out in interference pattern when hits screen



- **In 1905, Einstein proved that for phenomena such as the PhotoElectric Effect (principle upon which solar panels operate), light behaves like a particle → THE PHOTON**

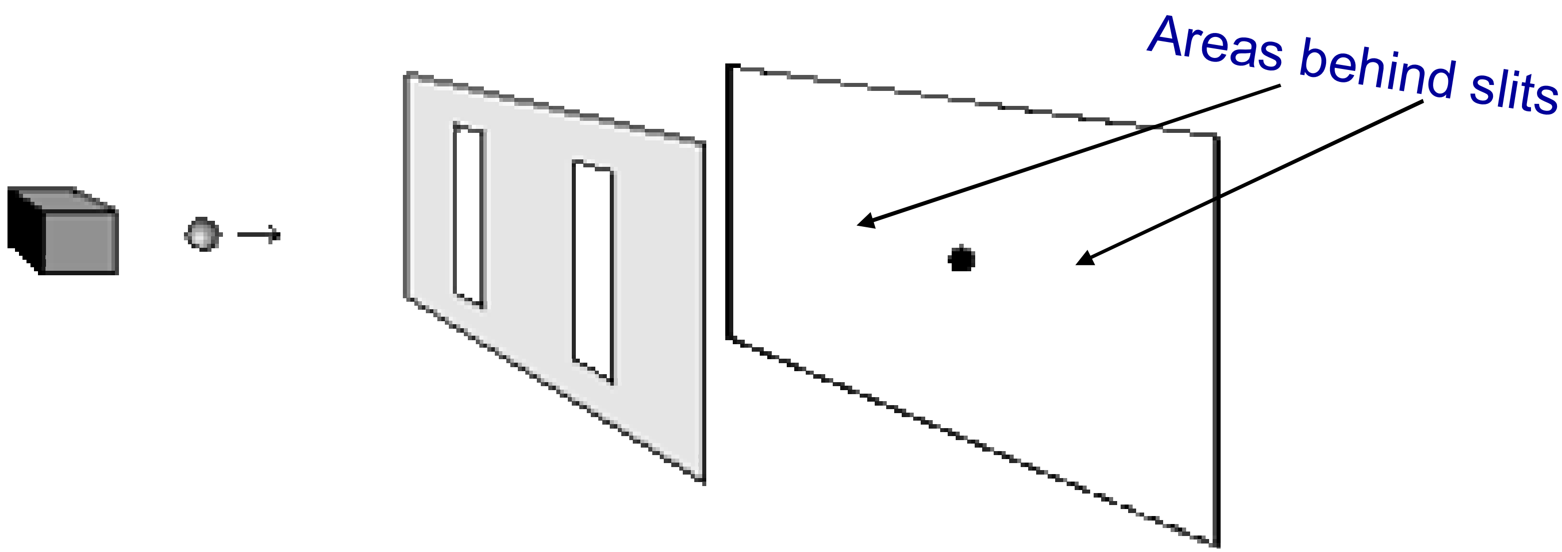


- **Fundamental nature of a particle:**
  - LOCALIZED to a certain position
  - Follows straight line paths
  - Does NOT spread out when it hits screen

Can Light be both Wave and Particle?

Repeat the experiment <u>one photon at a time</u>

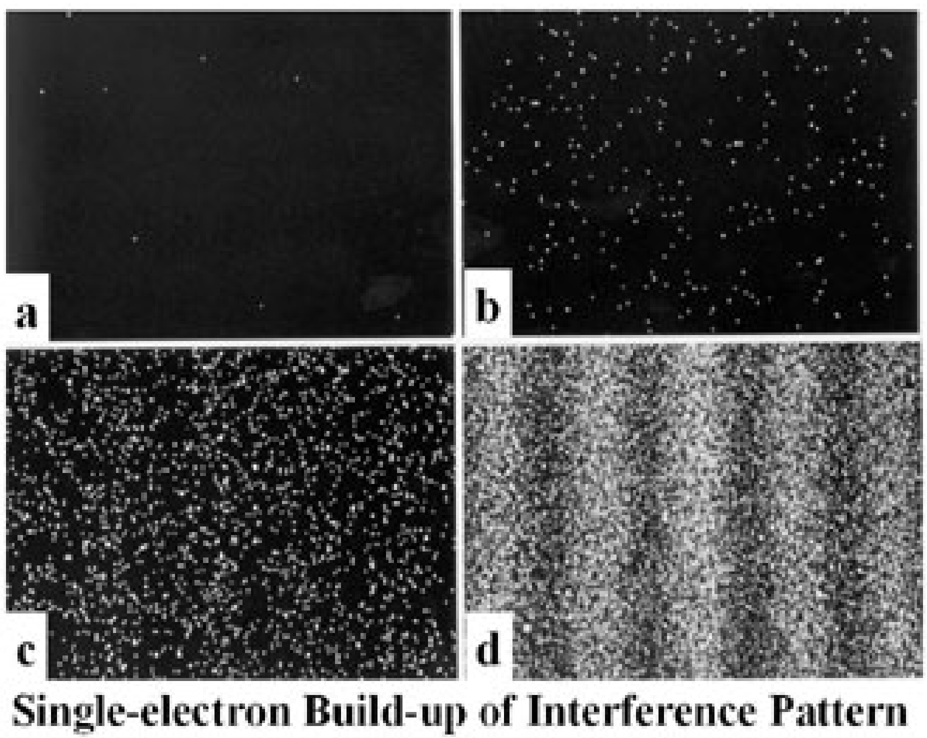
- Over time, the photons *only land on interference peaks characteristic of waves*, not in the troughs
  - consider the fact that they also pile up in the middle!
  - pure ballistic particles would land in one of two spots behind the slits



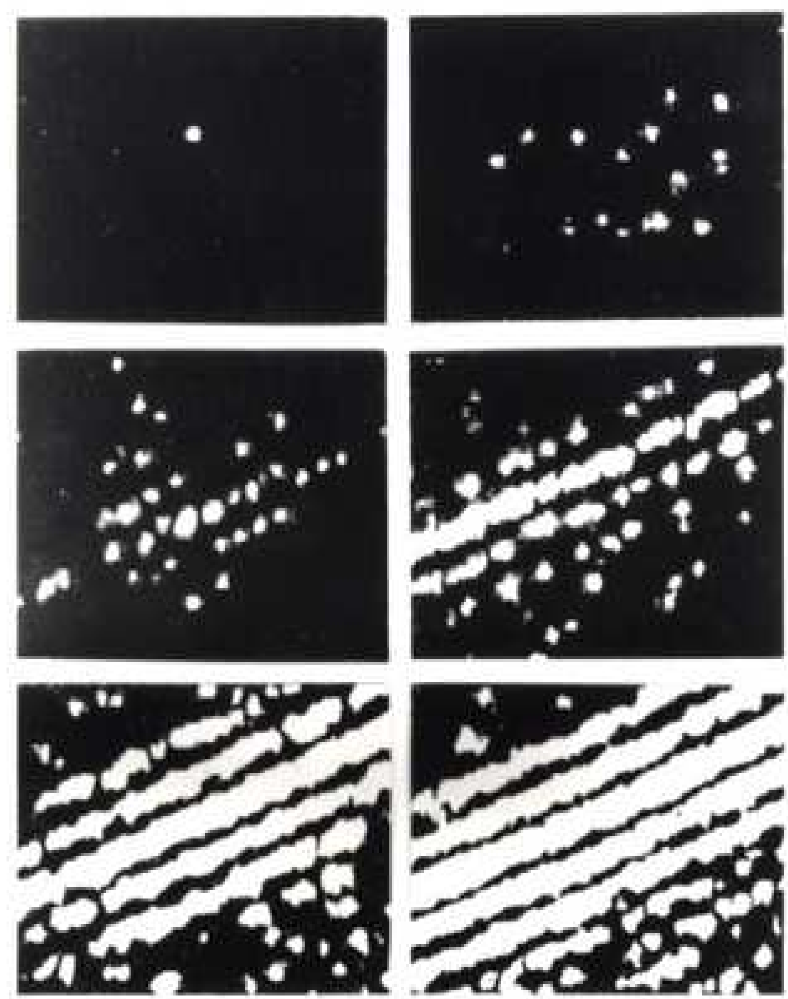
- **How did the photon "know" that second slit was open?**

2 Slit experiments with Electrons

- We normally think of electrons as particles, but they exhibit wave-like aspects too
- Actual images from experiments with electron beams



Hitachi 1989



Bologna 1974

Is Light a Wave or Particle?

Neither; Both; take your pick

- **Non-intuitive combination of wavelike *and* particle-like**
  - Appears to behave in wavelike manner
  - But with low intensity, see the interference pattern build up out of individual photons, arriving one at a time
- **How does the photon *know* about "the other" slit?**
  - Actually, it's *impossible* to simultaneously observe interference *and* know which slit the photon came through
  - Photon "sees", or "feels-out" *both* paths simultaneously!
- **Speak of wave-part describing *probability distribution* of where individual particles (photons or electrons) may land**
  - **Hence, Wave–Particle Duality, both natures together**

What is Wave – Particle Duality?

- **Wave–Particle Duality marked the end of the line for classical causality**
- In double slit experiments, we can know everything possible about initial conditions, and it is still impossible to predict correctly where an individual photon hits the screen
  - We know the pattern that large groups of photons will make, and their distribution in the pattern, but we have no way of knowing which photons will go where
  - All that we can say about a single photon is the PROBABILITY of finding it in a given place
- **Physicists could no longer accept the proposition that light is *either* a particle *or* a wave, because they had "proved" to themselves it was *both*, depending on how they looked at it**

Quantum Probabilities

Predicting Quantum Events

- **Quantum Mechanics** is a *well–defined procedure* which allows us to predict the *probabilities* of certain results
- **Quantum probabilities** follow *deterministic laws* in same way that macroscopic events follow deterministic laws in the classical world
  - There is a direct parallel. If we know enough about the initial conditions of an experiment, we can calculate, using Quantum Mechanics, the exact probability for a certain result to occur
- **Suppose we calculate 60% probability for a Photon to land in area A**
  - Does that mean it can land somewhere else?
  - Yes, there is a 40% probability that it will
  - What determines *where* the photon will land? **Only pure chance!**

Albert Einstein's famous quote (1926): *"God does not play dice with the universe",* expresses his rejection of the fundamental randomness in Quantum Mechanics. He argued that physical reality must be deterministic and causal, not based on probability.
Physicists reluctantly must reject this: God DOES play dice!

Quantum System and Observer are Inseparable

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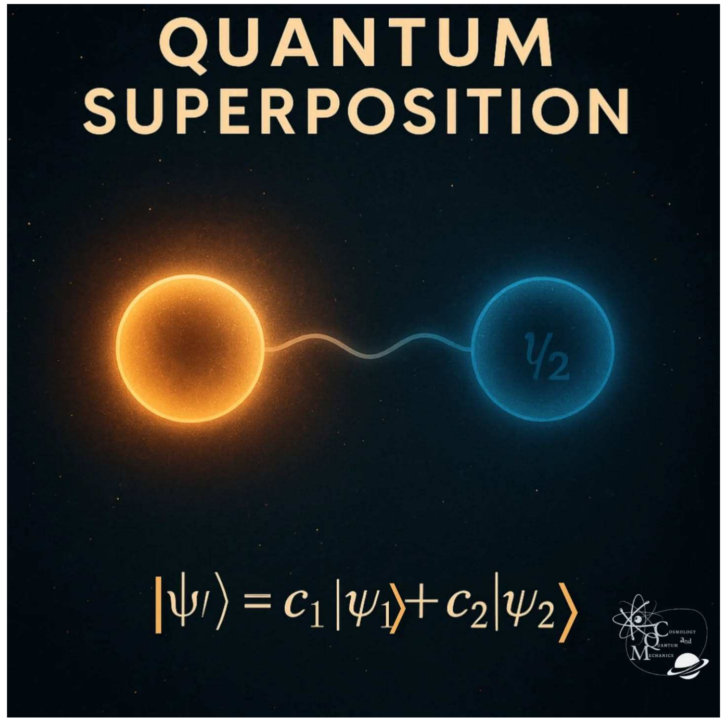
- **We traditionally divide the physical world into 2 parts:**
  - **Observed System:** e.g. a photon in 2 slit experiment
  - **The Observer:** e.g. a measurement device
- **Quantum domain:** the System and Observer <u>cannot be separated</u>
  - **The System *cannot* be observed until it *interacts* with the Observer, and even then all we can observe are its *effects* on the measuring device**
  - **Before we make a measurement**, the System propagates in isolation, and probabilities develop according to natural causal law. We CANNOT say exactly where the photon is during this time
  - **When we make a measurement,** we pick up ONE of the probabilities and can say the Photon is THERE, it is NO LONGER at any of the probable other locations!

Quantum Superposition of States

- **Once we have "prepared" the initial state of the Quantum System, there is dynamic unfolding of possibilities in accordance with the Schrődinger Equation**
  - e.g. the Photon may land at A <u>or</u> B

- ***Before* we do a measurement, the Photon is in a *Quantum Superposition* of probabilities at <u>both</u> A and B**
  - **However, it is not possible to measure the photon at both A and B <u>at the same time</u>**
  - **When ONE of these possibilities is actualized, the probability that the other one will occur becomes ZERO**



FB: Cosmology And Quantum Mechanics

Wave Functions

- The development of possibilities that takes place between the system initial state and measurement is represented by a particular kind of mathematical entity
  - **Physicists call this entity a "*Wave Function*" ψ**
  - The Schrődinger Equation governs the development of the Wave Function in time, which represents the evolution of probabilities of the isolated observed system
- **The Wave Function** represents ALL the possibilities that can happen to an observed system when it interacts with a measuring device
  - With the Schrődinger Equation and the Wave Function, we can calculate all of the probabilities of where a photon may land in a 2 slit experiment
  - **However we CANNOT predict with certainty where any individual photon may land**

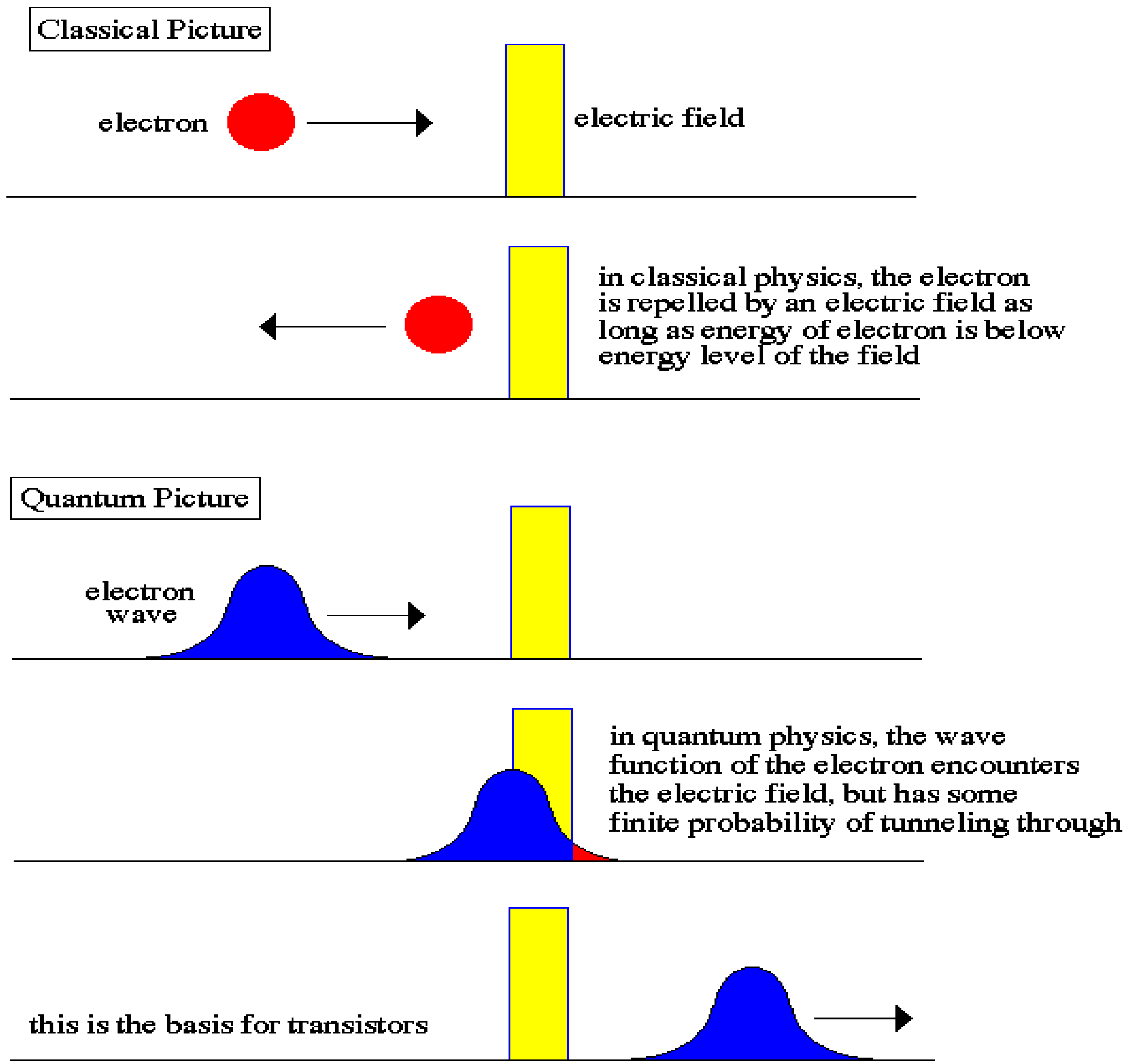
Quantum Tunneling

Quantum Tunneling occurs because of the specific mathematical properties of Wave Functions and the Schrodinger Equation

Only the “wall height” matters, not its thickness

Why do we not see tunneling in our daily lives?

If the wall is much thicker than the quantum wavelength, tunneling becomes improbable



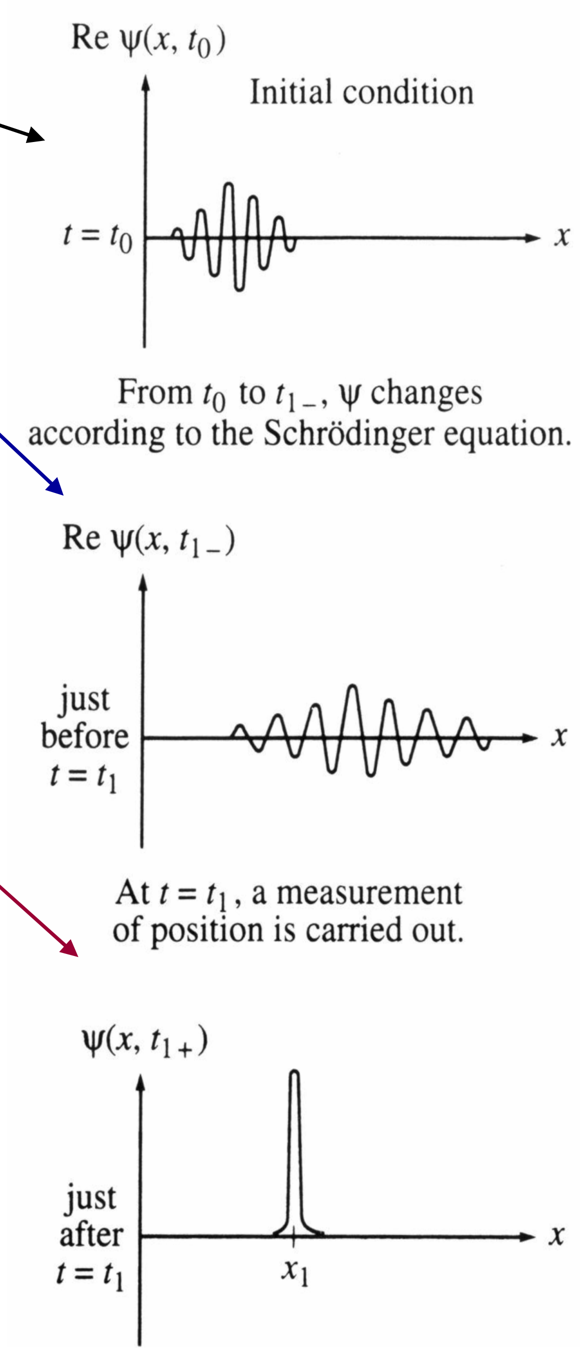
electron always repelled

electron usually repelled, but will occasionally pop out on the other side of the barrier, even though it does not have enough energy to do so classically

The Second Weirdness: What is “Real” in the Quantum World?

Wave Functions "Collapse"

1. The Quantum System is Initially Prepared
2. The system is then allowed to evolve with time
   - There is smooth and dynamic development, following the Schrődinger Equation
3. At the time of measurement, an abrupt and discontinuous change occurs, as one of the possibilities is actualized
   - **This abrupt change is called the COLLAPSE OF THE WAVEFUNCTION**
   - The Transition from 1→2 is called the Quantum Jump and is one of most debated concepts in Quantum Mechanics

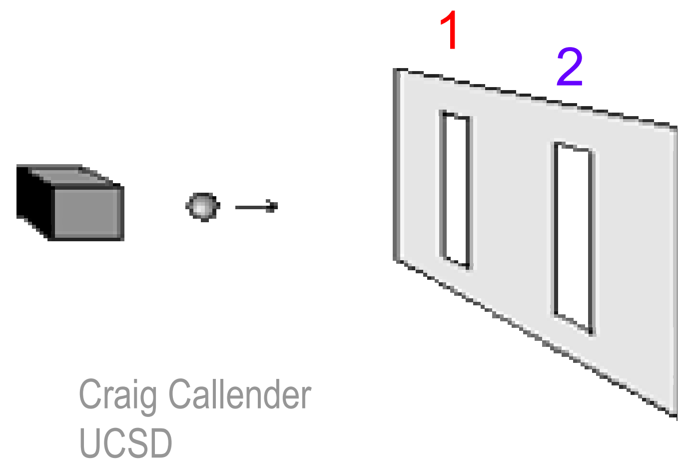


Quantum Mechanics, A. Goswami

Revisit the 2 Slit Experiment

Consider a 2 Slit Experiment with Automatic Photon Detectors

- **Light source emits a photon**
- The Wave Function of the photon contains the possibility that photon will pass through slit 1 and fire detector 1, and possibility that it will pass through slit 2 and fire detector 2
- **Now suppose detector 2 registers a photon**



- **According to Classical Physics:** the light source emitted a photon, which traveled from the source to the slit where detector 2 recorded it. Although we did not know its location while it was in transit, we could have calculated it, if we had enough information
- **According to Quantum Physics, this is NOT True:** No particle called a photon traveled between the light source and the screen. **There was NO photon until one actualized at slit 2.** Until then, there was ONLY a Wave Function, containing ALL of the probabilities of where a photon could be found. **In other words, until the measurement, all that existed were probabilities for a photon to actualize at either slit 1 or slit 2**

Our senses <u>do not</u> apply to the Quantum World

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- The problem is that we are used to looking at the world simply. We are accustomed to believing that something is there, or that is not there. Our experience tells us that the physical world is solid, real, and independent of us
- **Quantum Mechanics says, simply, that <u>this is not so</u>**
  - Strictly speaking, before the observation is made, the only thing that exists is the Wave Function, which encapsulates ALL of the possibilities of where the photon might be
  - The time evolution of these possibilities is the type of development governed by the Schrődinger Wave Equation
  - When the observation is made, all of the Wave Function, representing the observed system collapses, <u>except one part</u>, which actualizes into reality
  - There is NO way to know in advance which part of the Wave Function will actualize and the rest to vanish. The only law governing this phenomenon is statistical, i.e. **Random Chance**!

Schrődinger's Cat

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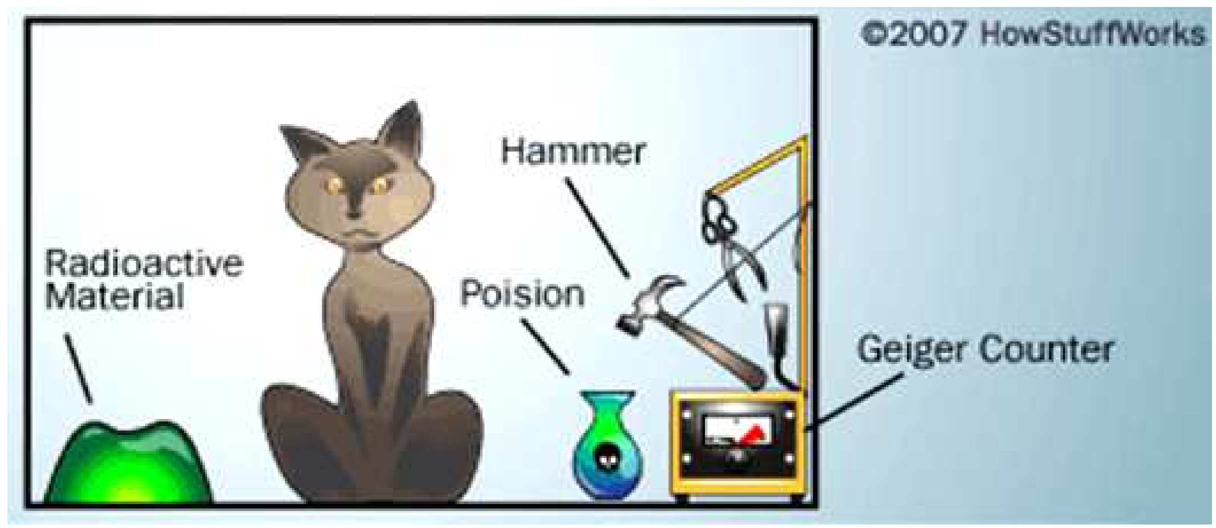
- **The various probabilities encapsulated in a Wave Function are held in a Quantum Superposition until one of them is realized (i.e. the Wave Function collapses)**
- Schrodinger's Cat is a thought experiment that illustrates the Quantum Superposition Principle, that a quantum system can exist <u>in multiple states at once</u>
- **Imagine a sealed, opaque box containing:**
  1. A live cat
  2. A small amount of radioactive material, with a 50% chance of decay in 1 hour
  3. A Geiger counter to detect the radioactive decay
  4. A vial of poison gas that breaks if the decay is detected



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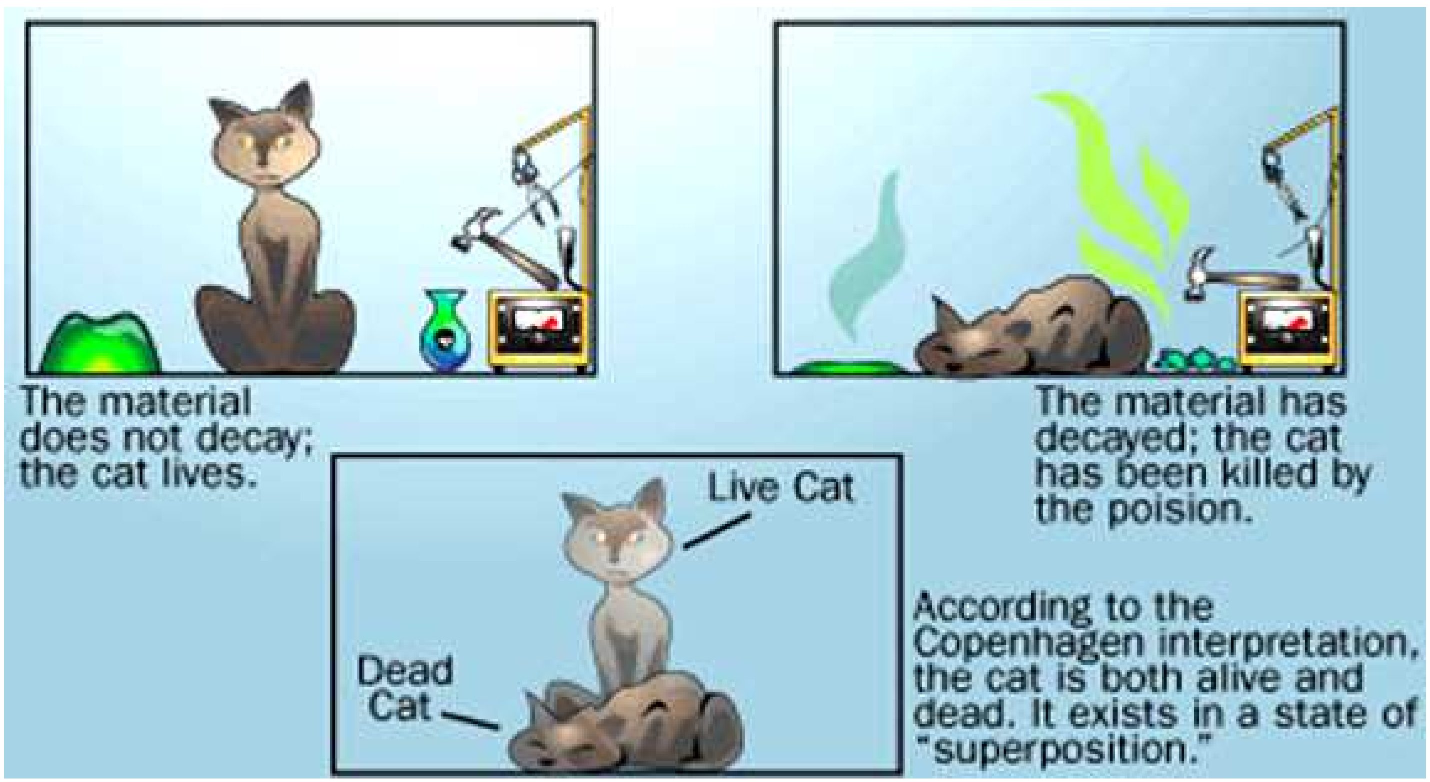
Schrődinger's Cat – Box Unopened

- Without opening the box, there is no way of knowing what happens inside it
- **According to Classical Physics:** the cat is either alive or it is dead
- **Copenhagen Interpretation of Quantum Mechanics:** the cat is in a kind of limbo represented by a Wave Function, which contains the possibility that the cat is dead and also the possibility that it is alive
  - **The cat is only alive or dead upon our opening the box!**



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Schrődinger's Critique

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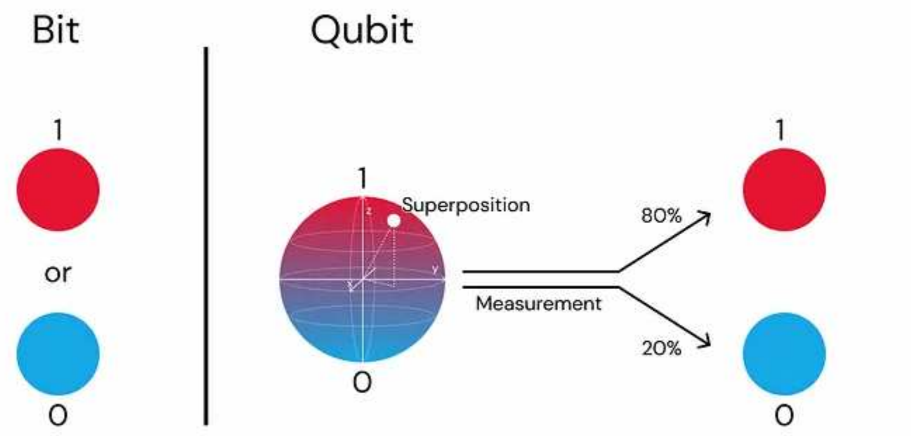
- **Schrödinger did not wish to promote the idea of dead-and-alive cats as a serious possibility; quite the reverse**
- The thought experiment serves to illustrate the bizarreness of Quantum Mechanics and the mathematics necessary to describe quantum states
- **Erwin Schrődinger (1935):**
  - *It is typical of these cases that an indeterminacy originally restricted to the atomic domain becomes transformed into macroscopic indeterminacy, which can then be resolved by direct observation. That prevents us from so naively accepting as valid a "blurred model" for representing reality. In itself, it would not embody anything unclear or contradictory. There is a difference between a shaky or out-of-focus photograph and a snapshot of clouds and fog banks.*
- These words summarize the uneasiness early physicists had with the Copenhagen Interpretation. Despite this, the Copenhagen Interpretation remains the most commonly held interpretation of Quantum Mechanics

The Key of a Successful Physical Theory

- **The value of a physical theory depends upon its USEFULNESS**
- Scientific change is often painful and slow, and many times scientists are forced to recon with conclusions required by data
- **Copernicus' idea that the Earth revolves around the Sun encountered much resistance**
  - **Goethe:** *Perhaps a greater demand has never been laid upon mankind; for by this admission [that the Earth is not the center of the universe], how much else did not collapse in dust and smoke…*
- **No physicist wanted to accept the implications of the Quantum World uncovered by Planck's initial discoveries**
  - **Heisenberg:** *when new groups of phenomena compel changes in pattern of thought . . . Even the most eminent of physicists find immense difficulties…*
- **As new theories demonstrate superior utility, their adversaries, however reluctantly, have little choice but to accept them. In so doing, they must also grant a measure of recognition to the world views that accompany them**

Application to Quantum Computing

- **In a conventional computer:** Bits can be in one of 2 possible states, which we denote as |0> and |1>



medium.com/@agarwalb

- **In a Quantum Computer:** prior to measurement, Qubits are in a superposition of both Quantum States at the same time

$$|\psi\rangle = c_0|0\rangle + c_1|1\rangle$$

$|\psi\rangle$ is the Quantum State of the Qubit

|0> |1> denote particular solutions to the Schrödinger equation weighted by the two Probability Amplitudes c_0 and c_1

- **Before the measurement occurs, the Qubit is in a SUPERPOSITION of both states**
- **This Superposition allows a Quantum Computer to compute all possible inputs at once, rather than separately**

The Third Weirdness: Entanglement of Quantum States

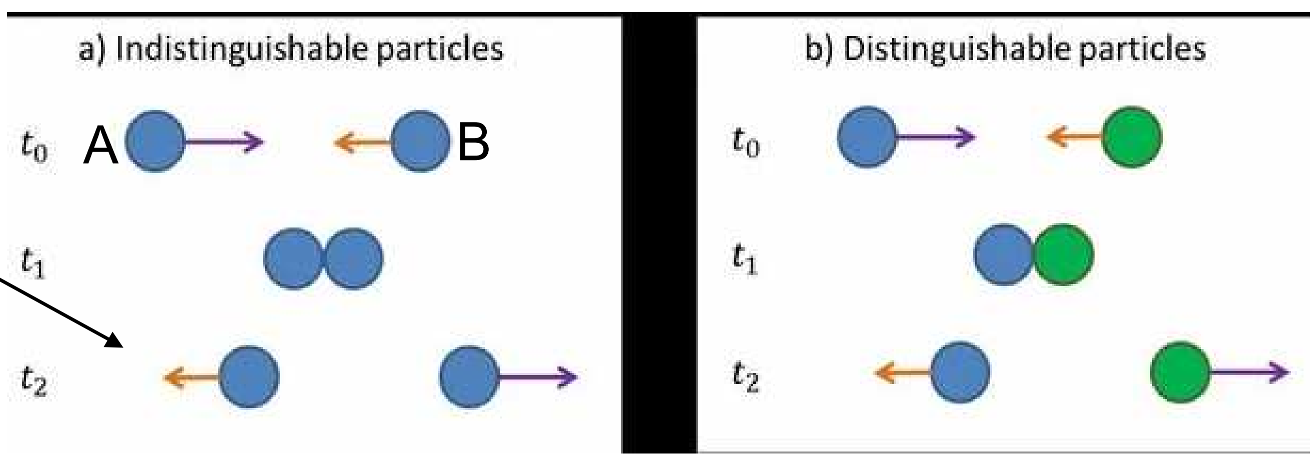
Chaos beneath Order

- **Classical View:** *Order beneath Chaos*
  - Beneath the prolific confusion of detail that constitutes our daily experience lie systematic and rational laws that relate all of them. → **This was essence of Newton's discovery**
- **Quantum View:** *Chaos beneath Order*
  - At the fundamental level, there is a confusion of continual creation, annihilation and transformation of subatomic particles
  - Above this confusion, limiting the forms that it can take, are a set of Conservation Laws
  - Conservation Laws do NOT specify what must happen, as ordinary laws of physics do. Rather, they specify what CANNOT happen
  - Quantum Theory provides the mathematical framework encapsulating these processes, with their respective probabilities

Quantum Indistinguishability

- **Heisenberg:** *Physicists who deal with the Quantum Theory are also compelled to use a language taken from ordinary life. We act as if there really were such a thing as an electric current [or a particle] because, if we forbade all physicists to speak of electric current [or particles] they could no longer express themselves*
- Therefore, we talk about subatomic particles as if they were real objects with an independent "objective" existence, even though this is not strictly true. Sometimes our everyday language is inadequate
- **Quantum Indistinguishability:**
  - Every particle of a given species is precisely identical. There is no "manufacturing tolerance". It is impossible to tell A from B

Is this particle A or B?
Answer:
it is IMPOSSIBLE to find out

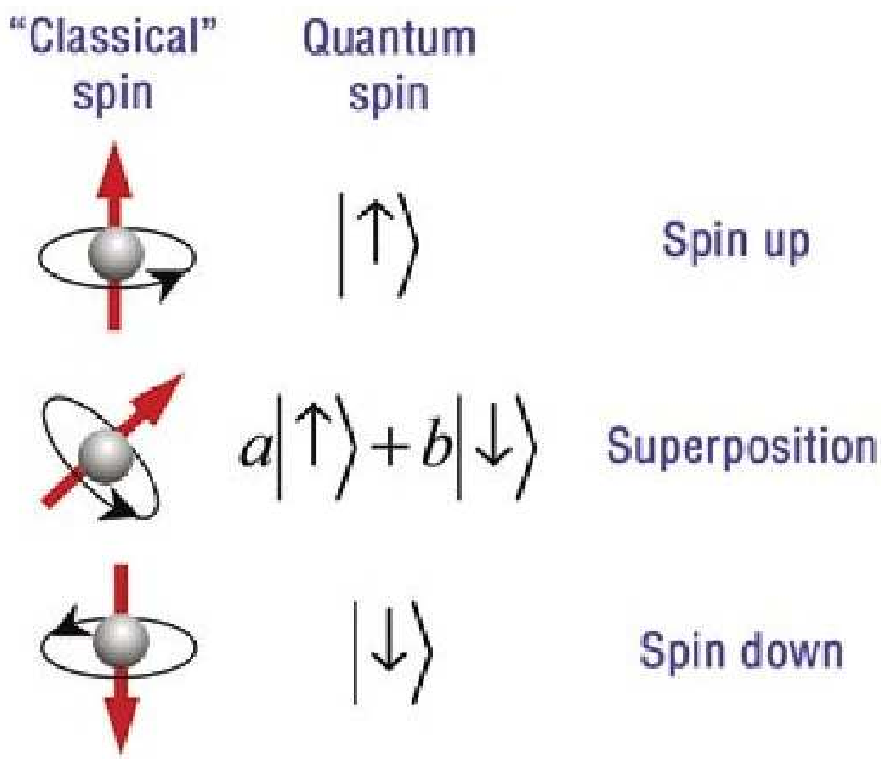


DOI: 10.13140/RG.2.2.17856.30727

Quantum Spin

- In addition to mass and electric charge, all subatomic particles have a third characteristic called SPIN, which is a mysterious type of angular momentum intrinsic to the existence of the particle

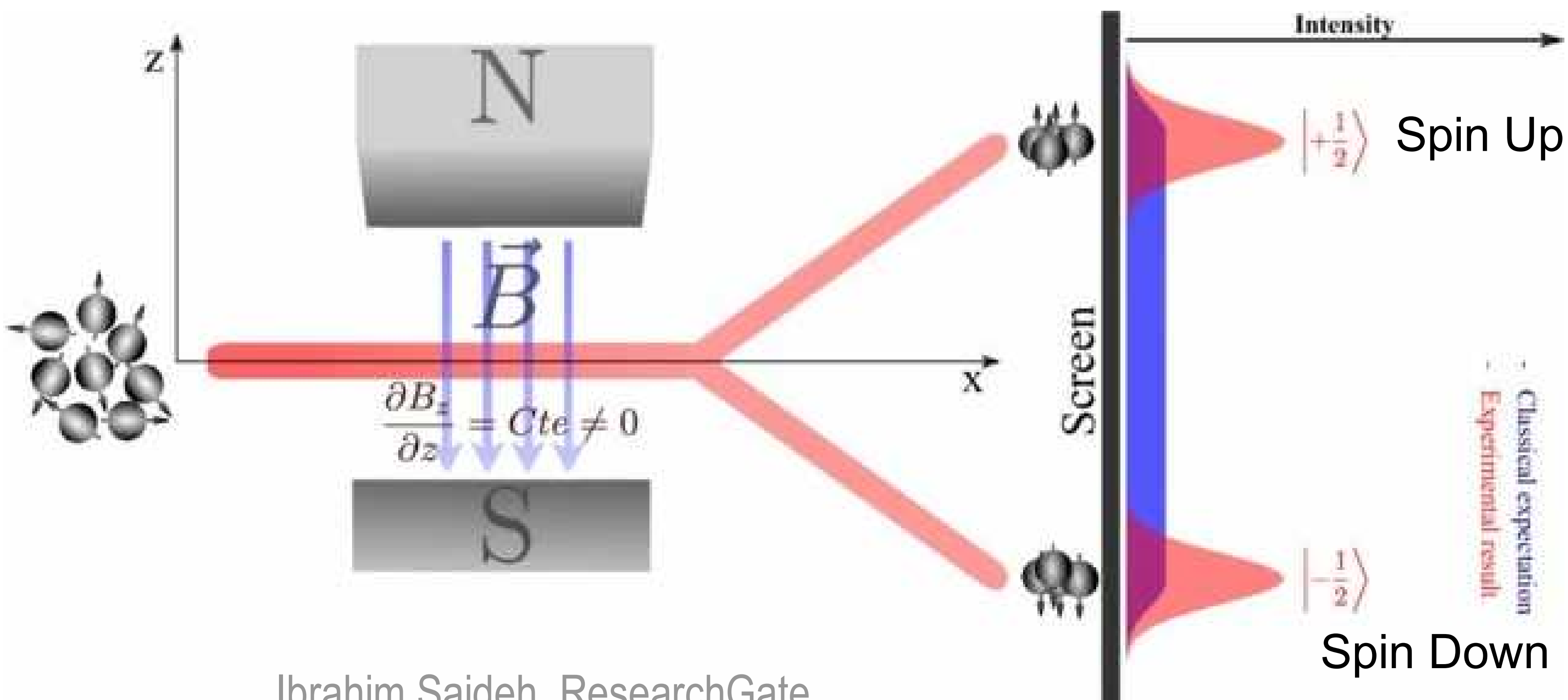
- All electrons carry Spin Quantum Number $S_e = ½$ and all photons have $S_\gamma = 1$ as part of their fundamental nature
- **Every subatomic particle, has a fixed, definite, and known angular momentum, but *<u>nothing is spinning</u>!***
- **Max Born:** *one should not imagine that there is anything in the nature of matter actually rotating*



A.S. Bracker et al., ResearchGate

Sorting Particles by Spin Orientation

- **The spin of a subatomic particle can be oriented by a magnetic field**
- If a beam of electrons with randomly oriented spin is sent through a particular type of magnetic field (called a Stern-Gerlach device), the magnetic field splits the beam into 2 smaller beams
- In one of them, all of the electrons have *Spin Up* and in the other all of the electrons have *Spin Down*



Ibrahim Saideh, ResearchGate

Two Particle Systems of Zero Spin

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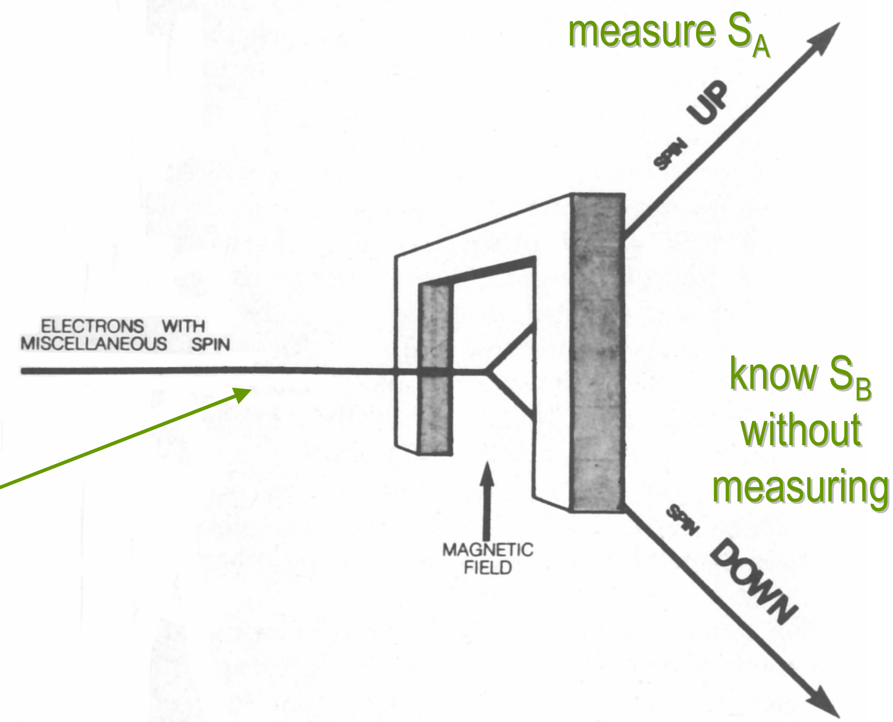
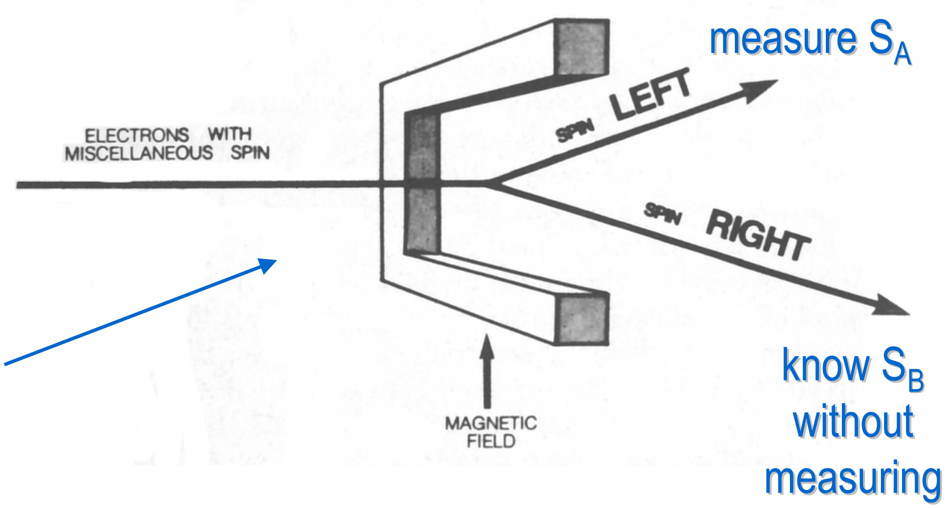
- **Suppose we have what is called a two-particle system of ZERO Spin**
  - This means the Spin of each of the particles in the system cancels the other $(S_A+S_B=0)$
- **If the magnetic field is oriented horizontally**, we can sort the electrons according to whether they have Spin UP or Spin DOWN
  - If we know Particle A has UP, we automatically know Particle B has spin DOWN *without measuring it*
- **Alternately, we can orient the field vertically** to sort the electrons according to Spin LEFT or Spin RIGHT
  - If we know Particle A has LEFT, Particle B *automatically* has to have Spin RIGHT





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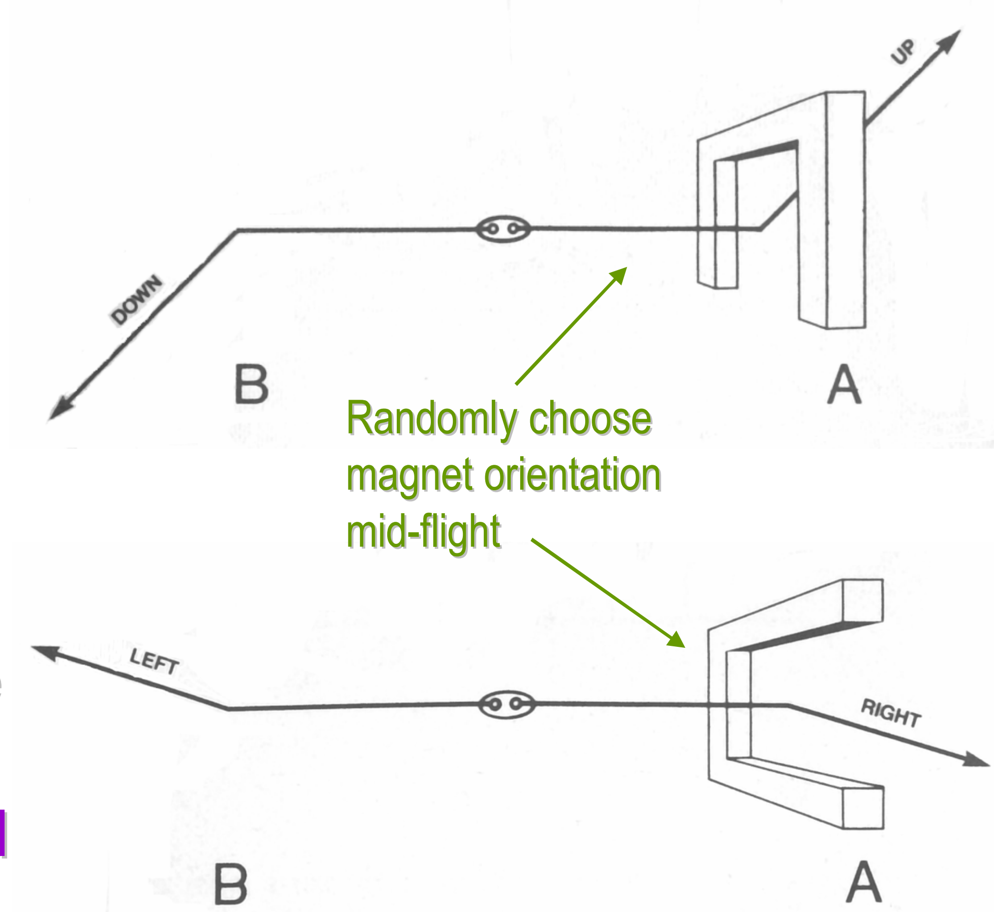
Now Comes the Weird Part

- **In 1935, Einstein, Podolsky and Rosen (EPR) came up with an experiment using spin states which they thought would indicate Quantum Theory is incomplete**
- Use the same two particle system of Zero Spin ($S_A+S_B=0$)
- While Electron A is in flight to the magnet, randomly switch its orientation from horizontal to vertical
- **Question:** Will the Electron B know that the magnet was switched, and orient its spin to the corresponding direction, even though A and B are not connected in any way?



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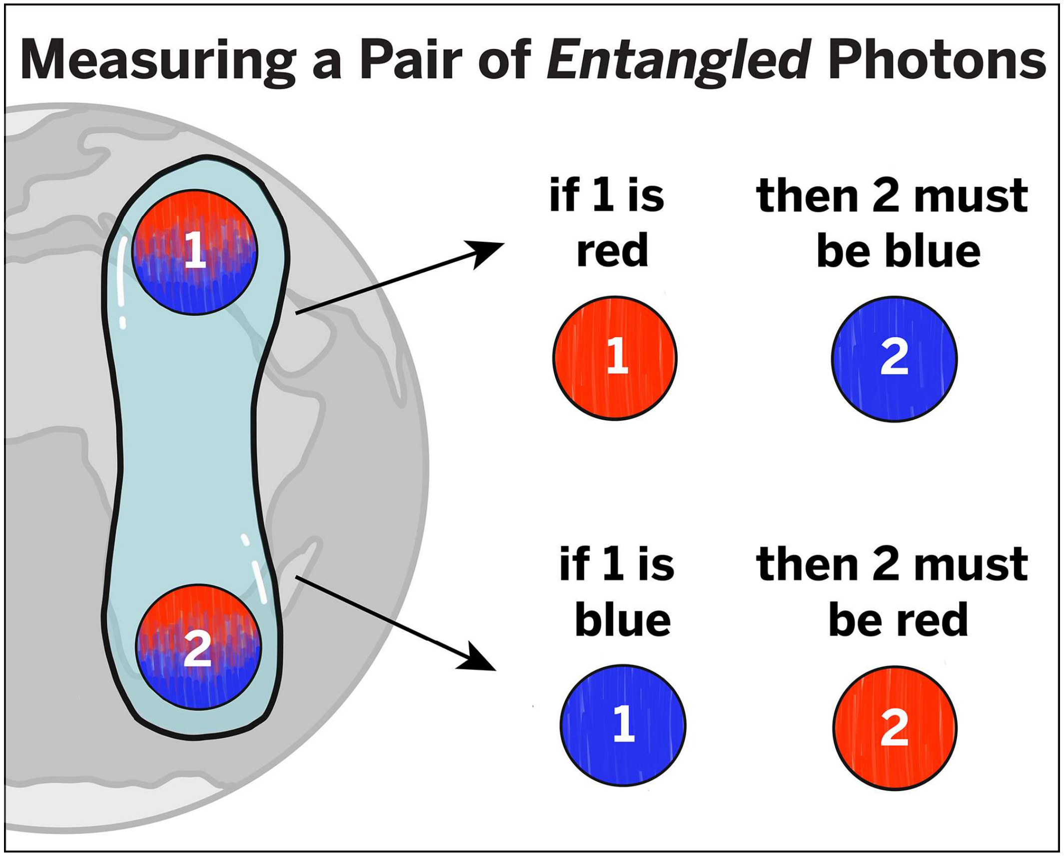
The Result Defies Common Logic

- Yes, Electron B "knew" the magnet orientation used to measure the spin of Electron A and behaved accordingly, in precise agreement with predictions of Quantum Mechanics
  - **Schrődinger:** *It is rather discomforting [in reference to this experiment] that the (quantum) theory should allow a system to be steered or piloted into one or the other type of state at the experimenter's mercy in spite of his having no access to it*
  - **Einstein** himself refused to accept the conclusion, arguing that somehow information must be traveling from A to B in a way that the experimenter mistakenly left in the experiment
  - The Einstein-Podolsky-Rosen (EPR) experiment has since been repeated many times, under increasingly strict conditions, and each time the predictions of Quantum Mechanics are correct
- **Rather than disproving the completeness of Quantum Mechanics, the EPR experiment inadvertently discovered the phenomenon of *Quantum Entanglement***

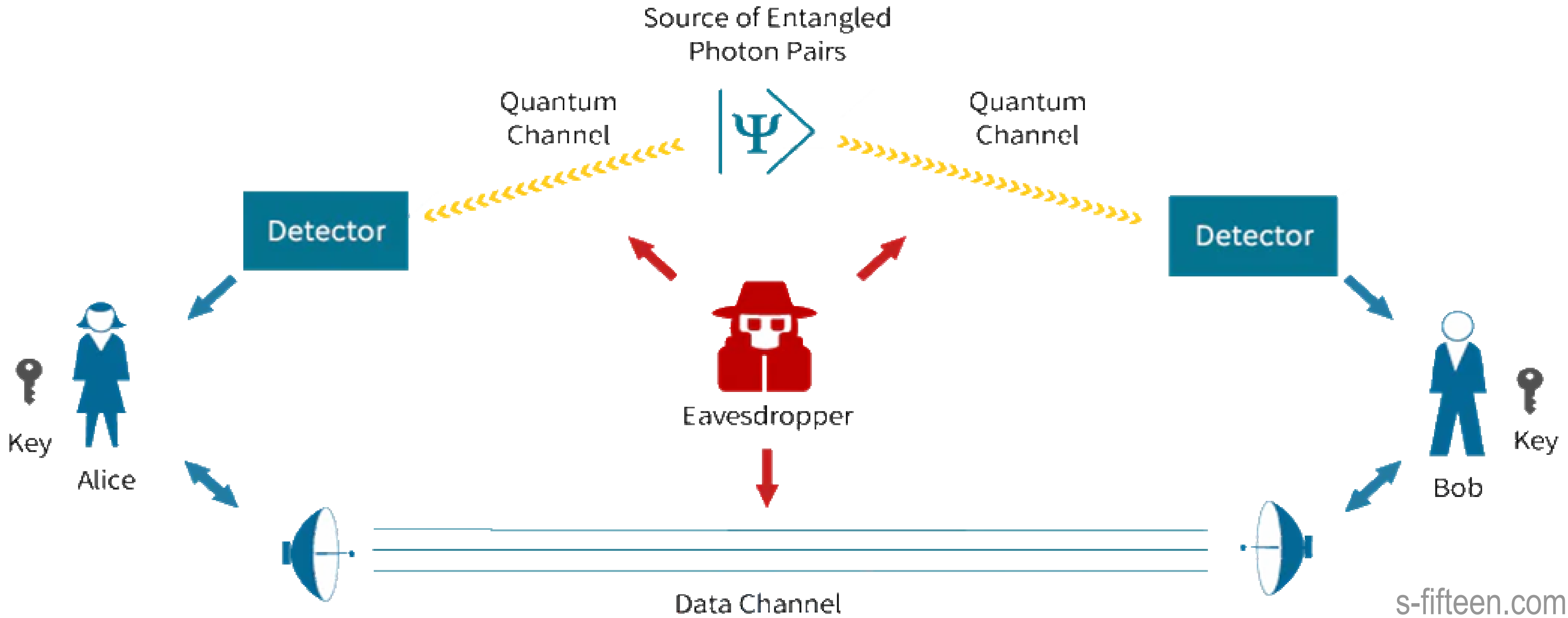
Quantum Entanglement

- **Quantum entanglement:** a physical phenomenon where pairs or groups of particles become linked such that their quantum states are interdependent, <u>regardless of the distance separating them</u>
- Measuring one particle <u>instantly</u> determines the state of the other, a "spooky" correlation that defies classical physics
- Quantum Entanglement has been demonstrated experimentally with photons, electrons, top quarks, and even molecules [source: Wikipedia]



quantumatlas.umd.edu

Application to Quantum Encryption



Schematic of a two-node implementation of Quantum Key Distribution

- Photons are distributed using a Quantum Channel, usually an optical link, and detected using single-photon detectors
- Parties follow a protocol allowing them to simultaneously generate identical keys at two distant locations by communicating measurement details over a data channel
- Security is guaranteed by Quantum Physics, which predicts that an Eavesdropper inadvertently produces detectable errors through their activities

The Victory of the Weird Theory

- **Without Quantum Mechanics, we could never have designed and built:**
  - semiconductor devices
    - computers, cell phones, etc.
  - lasers
    - CD/DVD players, bar-code scanners, surgical applications
  - MRI (magnetic resonance imaging) technology
  - nuclear reactors
  - atomic clocks (e.g., GPS navigation)
- In the future will come Quantum Computing and unbreakable Quantum Encryption
- **Physicists didn't embrace Quantum Mechanics because it was gnarly, novel, or weird**
  - **It's simply that the #$!&@ thing worked so well**

What does Quantum Mechanics Describe?

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- The acceptance of Quantum Mechanics did not come easily
- In 1927, physicists met to ask themselves what the new quantum physics meant. What they decided became known as the *Copenhagen Interpretation of Quantum Mechanics*
  - It marked the emergence of the new physics as a consistent way of viewing the world, and remains the most prevalent interpretation of the mathematics of quantum mechanics
- **In effect the Copenhagen Interpretation says:**
  - **We cannot say anything about why the quantum world follows such weird rules**
  - **<u>The only important thing</u> is that Quantum Mechanics works in all possible experimental situations.**
i.e. it correctly predicts the probabilities of certain quantum events occurring
- The scientific idea of an absolute truth that would allow knowledge of a universe with an independent existence from us has to be discarded for the quantum realm

Is Quantum Theory Complete?

- **Are we missing some fundamental piece of information**, which would enable us to predict exactly where the particle ends up, instead of a distribution of probable locations?
- **Copenhagen Interpretation of Quantum Mechanics says NO!**
  - Quantum Mechanical probabilities are the most that is knowable
  - It is NOT NECESSARY to make any statements about an underlying “physical reality”, just as long as Quantum Mechanics correctly predicts the probabilities observed when an experiment is repeated many times under identical condition
- **e.g. It is NOT necessary to know HOW light can manifest itself as both particles and waves.**
  - It is SUFFICIENT to know that light does this, and that we can use this phenomenon to correctly predict probabilities

Copenhagen Interpretation Summary (1)

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- In 1927, the most famous assemblage of physicists in history gathered in Brussels to debate and decide upon the interpretation of the new "Quantum Mechanics'"
  - Many famous debates between Einstein and Bohr ensued
  - The conclusions from this conference are named after Bohr's home town, and remain widely accepted today
- **Worldview:** Quantum Mechanics is <u>not</u> able to make definite statements about an underlying *physical reality*, but is restricted to making *statistical predictions* about the results of *specific experiments*
- **Correspondence Principle:** Quantum Mechanics must converge to Classical Mechanics in the limit where quantum effects can be disregarded

Copenhagen Interpretation Summary (2)

- **Principle of Inseparability:** it is not possible to decouple the physical system under investigation from the experimental apparatus used to make the measurements, and the interaction between the object and the apparatus forms an inseparable part of the results obtained
- **Bohr's Principle of Complementarity:** it is not possible to observe both the wave and particle aspects of a quantum system simultaneously. *Complementary experimental arrangements will yield complementary quantum phenomena*
- **Heisenberg Uncertainty Principle:** certain pairs of observables cannot be simultaneously measured with arbitrary exactness. Rather, the exactness of one observable will be inversely proportional to the exactness of the other

Copenhagen Interpretation Summary (2)

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- **Probability Interpretation:** the Quantum Mechanical Wave Function Ψ is not material in nature, but probabilistic. The amplitude of the wavefunction corresponds to a probability amplitude for the quantum system, and its absolute square $\Psi^{*}\Psi$ corresponds to a probability density
- **Superposition Principle:** a quantum state represented by a linear superposition of allowable quantum states is itself an allowable quantum state
- **Completeness Postulate:** *all* obtainable information about a quantum system is contained in its Wave Function Ψ
  i.e. there is *no missing information*