Where Are We, Really?
Parallel Universes, Fact or Fiction

Lecture 1: A Film – *Parallel Worlds, Parallel Lives*

Lecture 2: The Plurality of Worlds in Religion, Philosophy and Fiction – from Ancient Scriptures to Today’s Sci-Fi

Lecture 3: Science’s Parallel Worlds – the Many-Worlds Interpretation of Quantum Reality

Lecture 4: Science’s Parallel Worlds – the Multiverses of Big Bang and Inflation Theory, String Theory and M-Theory
“David believes in multiple universes—all of them lousy.”
listen, there’s a hell of a good universe next door –
let’s go

-- e.e. cummings
What’s a Parallel Universe?

- A hypothetical separate or alternate reality
  … Coexists with one’s own reality
What’s a Parallel Universe?

- A hypothetical separate or alternate reality
  … Coexists with one’s own reality

- What is reality?
  … Subjective vs. objective views
  … “Objective” view evolves throughout human history
Pre-Copernican View of the Universe
“Island Universe” c. 1880
The Modern View of the Universe

Sloan Digital Sky Survey Composite Image (each point of light represents a galaxy)
Max Tegmark

- Professor of Physics at MIT

- Classified parallel universe theories into 4 major categories or “levels”
# Tegmark’s Parallel Universe Levels

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Bibliography


Nicholas of Cusa (1401-1464)

- German Cardinal of the Roman Catholic Church

- Believed that the universe was actually infinite, without external limits (“privatively infinite”) as seen from the human point of view

- Held that the earth was not the center of the universe, because an infinite space can have no center

- Identified the metaphysically infinite with God and Truth; accepted that the infinite encompassed contradictions when considered from the finite human perspective
Giordano Bruno
(1548-1600)

- Italian priest and philosopher
- Deeply influenced by Nicholas of Cusa’s ideas on infinity and indeterminacy
- Developed a pantheistic philosophy of a transcendent, ineffable God Who contained contradictions because of His metaphysical infinity
- Held that the universe was actually infinite in space and time, that the Earth was not its center (following Copernicus) and that there were an infinite number of worlds besides Earth
- Charged with blasphemy and heresy and burned at the stake
In short then, to come straight to my proposition, it appeareth to me ridiculous to affirm that nothing is beyond the heaven …

Just as it would be ill were this our space not filled, that is, were our world not to exist, then, since the spaces are indistinguishable, it would be no less ill if the whole of space were not filled. Thus we see that the universe is of infinite size and the worlds therein without number.

-- Giordano Bruno
I can imagine an infinite number of worlds like the Earth, with a Garden of Eden on each one. In all these Gardens of Eden, half the Adams and Eves will not eat the fruit of knowledge, and half will. But half of infinity is infinity, so an infinite number of worlds will fall from grace and there will be an infinite number of crucifixions.

-- Giordano Bruno
H. G. Wells (1866-1946)

- Novelist, teacher, historian, journalist
- Along with Jules Verne and Hugo Gernsback, considered one of the creators of the genre of science fiction with works like *The Time Machine, The War of the Worlds*, and *When the Sleeper Wakes*
- Raised in poor circumstances, self-taught
- Had numerous affairs and illegitimate children
- Wrote *Men Like Gods* in 1923, the first novel to use the device of a parallel universe
Men Like Gods (1923)

- A depressed newspaperman and other Englishmen are accidentally transported to a parallel universe containing a world called Utopia with a world government, advanced science, no class distinctions, no diseases and no threats to human survival

- The newspaperman’s Victorian attitudes are changed by exposure to Utopia, but Utopians begin to fall ill

- The Utopians quarantine the Englishmen, who scheme to escape and take over Utopia, but the newspaperman reveals the plot to the Utopians

- Provoked Aldous Huxley into writing *Brave New World* as a riposte to what he saw as Wells’ utopian naivety
Murray Leinster
(William Fitzgerald Jenkins)
(1896-1975)

- American science-fiction and pulp fiction writer; Hugo award, 1956
- Coined the phrase, “first contact,” to describe the first encounter between humans and alien life forms; predicted the Internet in his 1946 novel *A Logic Named Joe*
- His *Sidewise in Time*, the first sci-fi story to explicitly incorporate alternate universes, appeared in the June 1934 issue of *Astounding Stories*
Sidewise in Time (1934)

- A mathematician at a small college determines that an apocalyptic cataclysm will destroy the universe.

- Sections of the earth’s surface begin changing places with their counterparts in alternate universes having different timelines.

- The mathematician leads a group of students to explore one such area; they find themselves isolated from their own timeline.

- The mathematician reveals his plan to lead the group to a more primitive timeline where he can use his knowledge to make himself the ruler.
Olaf Stapledon (1886-1950)

- Oxford MA; Ph.D., U. of Liverpool
- Conscientious objector during WWI
- Influenced Arthur C. Clarke, Virginia Woolf, Jorge Luis Borges, Bertrand Russell and Winston Churchill
- Wrote several philosophical works and novels including *Star Maker*, which C.S. Lewis described as "sheer Devil worship" and Arthur C. Clarke considered one of the finest science fiction works ever written.
Star Maker (1937)

- Deals with philosophical themes: the essence of life, birth, decay and death and the relationship between Creation and Creator

- An English narrator is transported out of body to another planet where his mind merges with one of that civilization’s inhabitants

- As they travel through the Universe, they merge with other life forms to form a group mind which eventually encounters the Star Maker, the Creator of the Universe, who evaluates its quality without any feeling for the suffering of its inhabitants

- Other Universes created by the Star Maker are then described
Level 1: Regions Beyond Our Cosmic Horizon

-Time since Big Bang: 13.7 billion years

- We can’t receive signals taking longer than 13.7 billion years to reach us

- The most distant visible objects are now about 42 billion light years away
- Initial distance right after Big Bang = 1 light second
- Recession velocity: 0.999993 c (99.9993% of the speed of light)
- Present time (13.7 billion years later) …

Total distance = 42 billion light years (drawing NOT to scale!)
Level 1 Parallel Universe

- If the universe is infinite, eventually everything is replicated

- The closest copy of you is about $10^{10^{29}}$ meters away

- The closest copy of the 42 billion light-year radius sphere surrounding the Earth is about $10^{10^{115}}$ meters away
Level 1 Parallel Universe

(r = 42 billion light years)

10^{10^{115}} meters
(10^{10^{113}} light years)

(Drawing not to scale)
A Closer Look at the Big Bang

- A gigantic cosmic explosion?

- Explosions are chaotic!
- Regions that can *never* have been in causal contact appear generally similar.
Large-scale shape of entire universe
(3rd spatial dimension suppressed)

Spherical universe (closed)

Hyperbolic Universe (open)

Flat universe

$-\Omega_0 = \text{ratio of average density of universe to critical density for universe to be flat} = \frac{\rho_{\text{avg}}}{\rho_{\text{critical}}}$
Level 2: Other Post-Inflation Bubbles

- *Inflation theory* explains
  ... Flatness of universe
  ... Universe-wide spatial isotropy and homogeneity
  ... Large scale structure of cosmic background radiation
Alan Guth

- Victor Weisskopf Professor of Physics, MIT; Dirac Medal, 2004
- Originator of inflation theory, along with Andrei Linde, Paul Steinhardt and Andreas Albrecht
- Won award for messiest office from Boston Globe
- Developed the theory when his research fellowship was on the verge of expiring and he had no teaching position lined up
- Calculated that a bubble universe can be created using about one ounce of matter and almost no energy
- “It is often said that there is no such thing as a free lunch, but the universe is the ultimate free lunch”

Alan Guth (1947 -)
Inflation

- Begins $10^{-35}$ seconds after start of Big Bang
- Lasts for $10^{-32}$ seconds
- Gravity becomes repulsive due to *inflaton field*
  … Large General Relativity cosmological constant
- Size of universe expands by $10^{50}$ times
- At end, potential energy of *inflaton field* converted into Standard Model particles
  … Quantum fluctuations at start become larger scale non-uniformities at end
SPECTACULAR REALIZATION:

The kind of supercooling can explain why the universe today is so incredibly flat, and therefore why it solves the fine-tuning paradox pointed out by Bob Dicke in his Einstein day lectures.

Let me first rederive the Dicke paradox. He relies on the empirical fact that the deceleration parameter today $q_0$ is of order 1.

$$q_0 = \frac{\dot{R}}{R^2}$$

Use the eqs of motion

$$3\dot{R} = 4\pi G (\rho + 3p) R$$

$$\frac{R^2 + k}{R^2} = \frac{3}{2}\rho R^2.$$ 

$$q_0 = \frac{1}{2} \left( 1 + \frac{3p}{\rho} \right) - 1 - 2\pi R^2$$

$$k R^2 = \frac{8\pi p}{3H^2} = \frac{8\pi p}{3H^2}$$

$$G = \frac{1}{H^2}, \ H = \frac{1}{R}$$

$$q_0 = \frac{4\pi}{3H^2} (\rho + 3p) - \frac{1}{H^2}$$

$$K R^2 = \frac{H^2}{(1 + 3p)} \left[ 2q - 1 - \frac{3p}{\rho} \right]$$

Using the above eq, the fact that $3p / \rho = 0$ for today's universe, and the fact that $q_0 \sim 1$, one has...
How Inflation Starts and Stops

1. Initial “False Vacuum” – inflation begins
2. Inflation continues – field undergoes “slow roll” down potential curve
3. Inflation ends – field reaches “true vacuum”, oscillates and gradually converts energy to particles
WMAP Cosmic Background Radiation Anisotropy Data

- Shows radiation averaging 2.7° K left over from Big Bang
  … “Ripples” are about +/- 1/10000°

WMAP = Wilkinson Microwave Anisotropy Probe
WMAP Data Power Spectrum

- Charts sizes of “ripples” vs. frequency of occurrence ($l$)
- Red line shows inflation theory’s prediction
Andrei Linde

- Professor of Physics, Stanford University; Dirac Medal, 2002

- With Alan Guth, Paul Steinhardt and Andreas Albrecht, originated inflation theory

- Developed the theory of eternal chaotic inflation and showed that inflation theory implied the existence of multiple universes

Andrei Linde (1948-)
**Bubble Universes**

- General inflaton field expands much faster than speed of light
- Bubble universes expand slower than speed of light

Bubble Universe (where inflation stopped)

Another Bubble Universe

General inflaton field (false vacuum)

Another Bubble Universe
Eternal Chaotic Inflation

- New “baby” universes randomly “bud” off “parent” universes and begin to inflate

- Each “baby” universe has different physical constants, may have different dimensions
  ... In string theory, extra dimensions may compactify differently (different Calabi-Yau shapes, different “brane” structures)

- Most “baby” universes inhospitable to life as we know it
Eternal Chaotic Inflation

7: Chaotic inflation produces local uniformity and global diversity in an infinite universe.

8: Eternal inflation predicts never-ending reproduction of inflating regions.
String theory

- Began in the late 1960s and early 1970s as an attempt to describe subatomic particles as vibrations of stringlike objects … Different vibrational modes equate to different particle characteristics … Purpose: Unify gravity with other physical forces

- Modern string theory ("M-theory") needs 10 space dimensions and 1 time dimension (11 total dimensions) … “Extra” dimensions may “compactify” into tiny (~10^{-34} cm) shapes called *Calabi-Yau manifolds*
Closed string vibrating in 3D
Example: string vibrational modes and particle mass

Low energy mode = low particle mass
Intermediate energy mode = intermediate particle mass
High energy mode = high particle mass

- Above illustration is for a closed string particle vibrating in 1-D only
Animation of 3-D projection of 6-D Calabi-Yau manifold
10-D space with 6 dimensions compactified in a Calabi-Yau manifold

- Compactified dimensions exist at all points in space
- They are shown at grid intersection points only for clarity
3-D projection of a 6-D Calabi-Yau manifold

- The pattern of holes in the manifold affects the vibrational patterns of the strings, which determines the quantum numbers of the particles (charge, spin, etc.)
3-D projection of another 6-D Calabi-Yau manifold

- There are millions of Calabi-Yau manifolds and very few criteria for choosing which one represents our universe
- It should have 3 holes, since there are 3 particle families
Branes

- Exist in M-theory
- N-dimensional “membranes” or hypersurfaces that are subsets of 11-dimensional spacetime (the “bulk”)
- Our universe is a 4-dimensional brane (or “D4-brane”)
- There may be other branes of varying dimensionality
- **Open strings** “live” on branes (are permanently attached)
  … If open strings represent normal matter particles and the strong, weak and electromagnetic force carrying particles, it means these are all are “stuck” in our own D4-brane
- **Closed strings** can move through the “bulk”
  … If closed strings represent gravitons, it means that gravitational forces can be felt across branes
  … Suggests a possible explanation for “dark matter”
Strings and branes in the bulk

Open strings (attached to brane)

Closed strings (can leave brane)

Another brane

The Bulk
Lisa Randall

- Professor of Physics, Harvard University
- Winner of Westinghouse Science Talent Search as high school student
- With student Raman Sundrum, authored seminal 1999 paper suggesting that extra dimensions did not need to be compactified and that gravity could move among branes while other forces would remain “stuck” to individual branes

Lisa Randall (1962-)
Randall-Sundrum Model (RS-1)

String size = $10^{-17}$ cm

String size = $10^{-32}$ cm

("Bulk")
Paul Steinhardt

- Albert Einstein Professor of Physics, Princeton University; Dirac Medal, 2002
- With Alan Guth, Andrei Linde and Andreas Albrecht, originated inflation theory
- With Neil Turok of Cambridge, developed the ekpyrotic universe theory, in which the big bang is replaced by a cyclic collision between branes (with a cycle time approximating 1 trillion years)

Paul Steinhardt (1954-)
Two Branes Colliding in the Bulk

- The distance between the branes in the bulk may be about 0.1 millimeter
Level 3: The Many Worlds of Quantum Physics

- Key concepts: superpositions, entanglement, decoherence

- **Superpositions** represent the results of events or actions in the world with more than one possible outcome

- **Entanglement** occurs when the different elements involved in a superposition evolve over time

- **Decoherence** results when an entanglement breaks down due to interaction with the world outside the superposition

- Quantum mechanics notation:
  
  \[ |X> \] = a vector for the quantum state of an event or action
  
  \[ \psi \] = the wavefunction representing how the quantum state of the event or action (or superposition) changes over time
Founders of Quantum Mechanics

Niels Bohr (1885-1962)
Werner Heisenberg (1901-1976)
Erwin Schrödinger (1887-1961)
I think it is safe to say that no one really understands quantum mechanics. Do not keep saying to yourself, if you can possibly avoid it, “How can it possibly be like that?” No one knows how it can possibly be like that.

-- Richard Feynman
The more success the quantum theory has had, the sillier it looks.

-- Albert Einstein

I do not like it, and I am sorry I ever had anything to do with it.

-- Erwin Schrödinger
Superposition: Schrödinger’s Cat

- $a^2 = \text{probability that material does not decay}$
- $b^2 = \text{probability that material does decay}$

- $a(|\text{Alive}\rangle_{\text{Cat}}) + b(|\text{Dead}\rangle_{\text{Cat}})$

- What happens when an Observer looks in the box?
Superposition

\[ a(|\text{Alive}_\text{Cat}\rangle) + b(|\text{Dead}_\text{Cat}\rangle) \]

Amplitudes:

\[ a = \cos 45^\circ = \frac{1}{\sqrt{2}} \]
\[ b = \sin 45^\circ = \frac{1}{\sqrt{2}} \]
Copenhagen Interpretation of Superposition

- Developed by Niels Bohr and Erwin Schrodinger in the 1920’s
- Suppose we do the Schrodinger’s Cat experiment with result:
  \[ a(|\text{Alive}\rangle_{\text{Cat}}) + b(|\text{Dead}\rangle_{\text{Cat}}) \]
- The superposition “collapses” – only the highest probability outcome is actually observed
  … If \( a^2 = b^2 \): Observer may see either a live or a dead cat but not both (one is randomly chosen)
- What causes the superposition to “collapse”?
  … It’s a mystery!
I am convinced that at any rate, [God] does not play dice.

-- Albert Einstein

… The being with a consciousness must have a different role in quantum mechanics than the inanimate object.

-- Eugene Wigner
(Nobel Prize, 1963)
Hugh Everett III

- Developed a new interpretation of quantum mechanical superposition to address the objections to the Copenhagen interpretation – the “relative state” formulation – as his 1957 Princeton Ph.D thesis

- Left physics when his ideas were not accepted by Niels Bohr and other mainstream physicists

- Bryce deWitt popularized Everett’s theory as the “Many-Worlds Interpretation” of quantum mechanics starting in the early 1970’s

- Today Everett’s theory is the foundation of quantum computing based on later work by David Deutsch and others
Everett’s “Many-Worlds” Interpretation of Superposition

- Again, suppose we have the result of the Schrodinger’s Cat experiment:
  … The Observer’s state is entangled with the cat’s state
  … \( a(|\text{"Alive"}>_{\text{Observer}} |\text{Alive}>_{\text{Cat}}) + b(|\text{"Dead"}>_{\text{Observer}} |\text{Dead}>_{\text{Cat}} \)

- Both parts of the superposition exist in separate universes
  … Each universe has a version of the Observer, the box and the cat
  … In one universe, the Observer sees a live cat
  … In the other universe, the Observer sees a dead cat

- The superposition never “collapses”
Everett’s “Many-Worlds” Interpretation of Superposition

A representation of the split that occurs based on the possible outcomes for each action, according to Everett’s Many-Worlds interpretation (courtesy of Max Tegmark).
Evidence for the Many-Worlds Interpretation

- Quantum interference effects
  … Multiple slit experiments

- Quantum computing
Quantum Interference Effects

- What is interference?
The Double-Slit Experiment
The Double-Slit Experiment

- If a wave is aimed at two closely spaced slits an interference pattern will result at a detector on the other side of the slits.
The Double-Slit Experiment

- If electrons are aimed *one by one* at two closely spaced slits an interference pattern will *gradually build up* on a detector on the other side of the slits.

- What is interfering with the electrons?
The Source of the Interference in The Double-Slit Experiment

- Classical physics: Total probability conceptually depends on adding individual probabilities that electron goes thru each slit:

\[ P(\text{Right Slit}) + P(\text{Left Slit}) \]

- Quantum physics: Total probability conceptually depends on squaring the sum of the amplitudes for each electron!

\[
\begin{align*}
[a(\text{Right Slit}) + b(\text{Left Slit})]^2 &= \\
a(\text{Right Slit})^2 + b(\text{Left Slit})^2 + 2a(\text{Right Slit})b(\text{Left Slit}) &= P(\text{Right Slit}) + P(\text{Left Slit}) + \text{interference}
\end{align*}
\]
The Source of the Interference in The Double-Slit Experiment

- State vectors: $|\text{Slit 1}\rangle + |\text{Slit 2}\rangle$
- Amplitude of electron thru Slit 1 = $a$; thru Slit 2 = $b$
- Detector is oriented in the $y$-axis direction

-To get the wavefunction, multiply by the complex conjugate:

$$|\Psi\rangle = (e^{iay} + e^{iby})(e^{-iay} + e^{-iby})$$

$$= e^{iay}e^{-iay} + e^{iay}e^{-iby} + e^{iby}e^{-iay} + e^{iby}e^{-iby}$$

$$= 2 + e^{iay}e^{-iby} + e^{iby}e^{-iay}$$

$$= 2 + e^{i(a-b)y} + e^{i(b-a)y}$$

$$= 2 + 2 \cos (a-b) y$$

$$= 2[1 + \cos (a-b) y]$$

If one hole is shut, no interference

Zeroes of $2[1 + \cos (a-b) y]$ represent dark places on interference pattern (where no electrons hit screen)
The Double-Slit Experiment and the Many-Worlds Interpretation

- Consider the experiment from a quantum point of view:
  ... $a^2 = \text{probability that electron goes through right slit}$
  ... $b^2 = \text{probability that electron goes through left slit}$
  ... Outcome of experiment is a superposition:
    \[ a(|"Right Slit">_{\text{Observer}} |Right Slit>_{\text{Electron}}) + b(|"Left Slit">_{\text{Observer}} |Left Slit>_{\text{Electron}}) \]

- The two parts of the outcome superposition both exist simultaneously and interfere with each other
  ... Where do they exist? – In parallel universes!
David Deutsch’s Four-Slit Experiment

- Photons are shot one at a time at the apparatus
- Compare the interference pattern caused by 4 slits (a) with the pattern caused by 2 slits (b)

- Notice what happens at point x
  … “Something” is coming through 2 of the slits to interfere with the photons coming through the other 2 slits and prevent them from reaching point x
Let us take stock. We have found that when one photon passes through this apparatus,
-- It passes through one of the slits, and then something interferes with it, deflecting it in a way that depends on what other slits are open;
-- The interfering entities have passed through some of the other slits;
-- The interfering entities behave exactly like photons …
… except that they cannot be seen.

-- David Deutsch
Quantum Computing

- Initially proposed by Richard Feynman in 1982

- Main component: **qubit** = a superposition of 0 and 1
  ... $|\Psi> = a|0> + b|1>$  ($a^2 + b^2 = 1$)

- Preparing a qubit
  ... Normal mirror = black
  ... Semi-silvered mirror = grey (reflects 50%, transmits 50%)

![Diagram of photon and qubit](image-url)
Applications of Quantum Computing

- Factorizing large numbers
  ... Classical computing: Divide by each possible factor starting with 2 up until square root of number
  ... Rapidly becomes intractable as numbers get larger

- Public key cryptography: RSA algorithm
  ... Invented by Ronald Rivest, Adi Shamir and Leonard Adelman in 1978
  ... Encrypts secure information on Internet today
  ... Uses large (128-bit, 256-bit, 512-bit) numbers as keys
  ... Decrypting requires knowing numbers’ secret factors
Peter Shor

- Bell Labs, 1987-2003; Professor of Mathematics, MIT, 2003-; MacArthur Fellow, 1999

- Developed **Shor’s algorithm** for using quantum computation to find factors of very large numbers
Breaking the Code – Shor’s Algorithm

- Suppose \( n \) is the number we want to factor

- From number theory we know \( x^a \mod n \) is periodic when the greatest common divisor of \( x \) and \( n \) is 1

- Suppose the period of \( x^a \mod n \) is \( r \): then,
  ... \( x^0 \mod n = 1 \) (since \( x^0 = 1 \)); \( x^r \mod n = 1 \); \( x^{2r} \mod n = 1 \); etc.

- Then:
  ... \( x^r = 1 \mod n \)
  ... \( (x^{r/2})^2 = x^r = 1 \mod n \)
  ... \( (x^{r/2})^2 - 1 = 0 \mod n \)
  ... If \( r \) is even, \( (x^{r/2} - 1)(x^{r/2} + 1) \) is an integer multiple of \( n \)
  ... As long as \( |x^{r/2}| \) is not 1, one of these must have a common factor with \( n \)

- Shor’s algorithm uses quantum computing to find \( r \)
Breaking the Code – Shor’s Algorithm

- Make a’s from the integers 1 thru q -1 such that \( n^2 \leq q \leq 2n^2 \)
- Prepare a superposition \(|a>\) of all the a’s in R1 (\( b = \) number of qubits required to represent superposition)
- Calculate \( x^a \mod n \) on \(|a>\) and place the resulting superposition \(|k>\) in R2
- The qubits in R1 (\(|a>\)) and R2 (\(|k>\)) are now *entangled*
Breaking the Code – Shor’s Algorithm

- Measure R2
  … Sets value of k
  … Also sets R1 to superposition of states consistent with k: c, c + q/r, c + 2q/r, etc. where c is the lowest integer such that \( x^c \mod n = k \)

- Performing a quantum discrete Fourier transform on R1 and measuring R1 then yields q/r

\[
|x^a \mod n> = |k>
\]

\[
\text{QDFT (R1)} = |q/r>
\]
Breaking the Code – Shor’s Algorithm

- When a large number (512 bits) is factored using this algorithm, there are \( \sim 10^{500} \) interference terms in the superposition calculations
  … Where are those calculations being done in reality?
  … There are only about \( 10^{80} \) atoms in the entire visible universe!

- Aren’t the interference terms of the superpositions really being processed in parallel universes?
Tegmark’s Parallel Universe Levels

- Level 1: Regions beyond our cosmic horizon
  ... Assumptions: Infinite space, same laws of physics

- Level 2: Multiple Post Big-Bang “Bubbles”
  ... Assumptions: Chaotic inflation after Big Bang, same fundamental physics equations but each bubble may have different physical constants or dimensions

- Level 3: The many worlds of quantum physics
  ... Assumptions: All possible outcomes of superpositions actually occur in parallel universes; decoherence experimentally verified in quantum computing
  ... Can coexist with Level 1 or Level 2

- Level 4: Other mathematical structures
  ... Assumptions: String theory: Mathematical existence = physical existence
Suppose a scientist, John (J), is attempting to measure the spin of an electron (E), which can either be up or down.

If everything were completely deterministic and John’s apparatus were 100% accurate there would be two possibilities --
\[ |\text{Ready}_J\rangle |\text{Spin-up}_E\rangle \rightarrow |”\text{Spin-up}”_J\rangle |\text{Spin-up}_E\rangle \]
\[ |\text{Ready}_J\rangle |\text{Spin-down}_E\rangle \rightarrow |”\text{Spin-down}”_J\rangle |\text{Spin-down}_E\rangle \]

But quantum mechanics says the electron is in a superposition:
\[ a(|\text{Spin-up}_E\rangle) + b(|\text{Spin-down}_E\rangle) \]
\[ a^2 \text{ and } b^2 \text{ are the probabilities of the respective states} \]

So when John is ready to start the experiment the initial state is:
\[ |\text{Ready}_J\rangle [a(|\text{Spin-up}_E\rangle) + b(|\text{Spin-down}_E\rangle)] \]

After the experiment the result is also a superposition:
\[ a(|”\text{Spin-up}”_J\rangle |\text{Spin-up}_E\rangle ) + b(|”\text{Spin-down}”_J\rangle |\text{Spin-down}_E\rangle) \]
Copenhagen Interpretation of Superposition at Outcome of Experiment

- This interpretation was developed by Niels Bohr and Erwin Schrodinger in the 1920’s

- Suppose we have the result of John’s experiment:
  \[ \ldots a(|“Spin-up”\rangle_j|Spin-up\rangle_E) + b(|“Spin-down”\rangle_j|Spin-down\rangle_E) \]

- The superposition “**collapses**” and only the highest probability outcome is actually observed in the (single) universe
  \[ \ldots \text{If } a^2 > b^2 \text{ then John would observe “Spin-up”} \]
  \[ \ldots \text{If } a^2 < b^2 \text{ then John would observe “Spin-down”} \]
  \[ \ldots \text{If } a^2 = b^2 \text{ then John may observe either “Spin-up” or “Spin-down” but not both (one is } \text{randomly chosen}) \]

- What causes the superposition to “collapse”?
  \[ \ldots \text{It’s a mystery!} \]