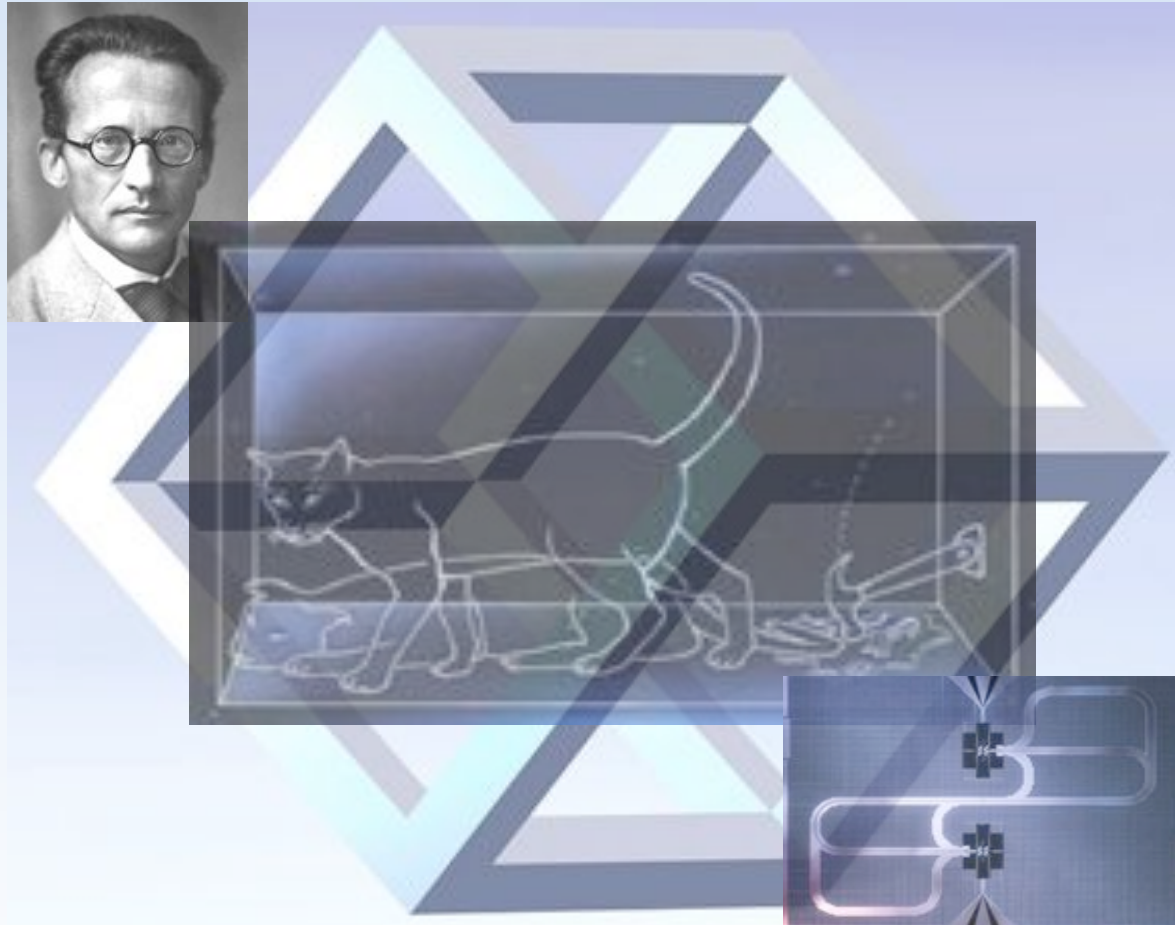
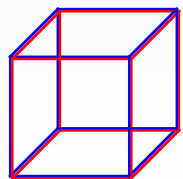


# ***Entanglement:***

## ***Schrödinger's Quirky Quantum Conundrum***

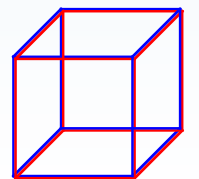


Frederick W. Strauch



Sigma Xi Talks

November 17, 2011



# *Thank you very much!*

- Williams College
- Physics Department
- Jay Pasachoff + Sigma Xi
- Students, especially:
  - *Teng Jian Khoo '09*
  - *Chris Chudzicki '10*
  - *Steve Jackson '10*
  - *Samyam Rajbhandari '11*
  - Douglas Onyango '11
  - Hai Zhou '11
  - Ben Athiwaratkun '12
  - Qiao Zhang '13

## Funding:

Research Corporation

National Science Foundation

## Collaborators:

Kurt Jacobs

(UMass Boston)

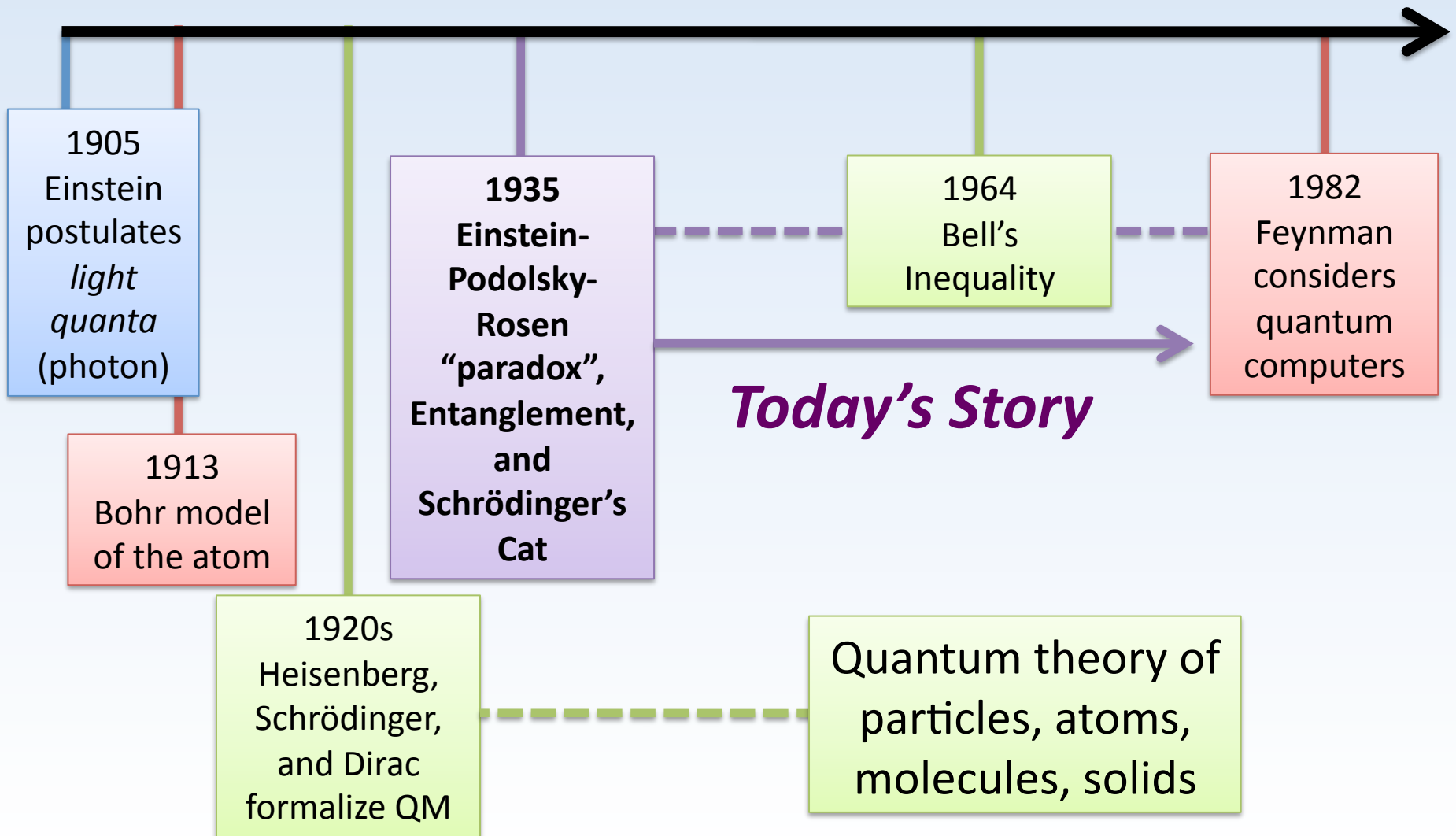


Ray Simmonds

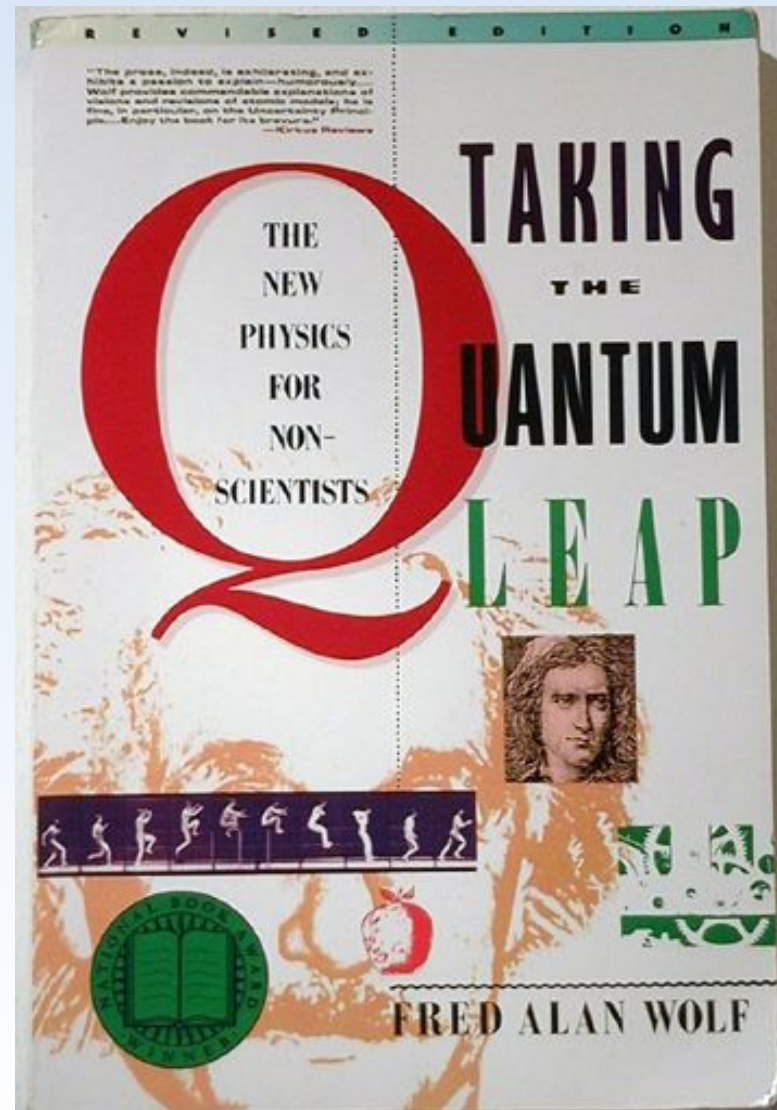
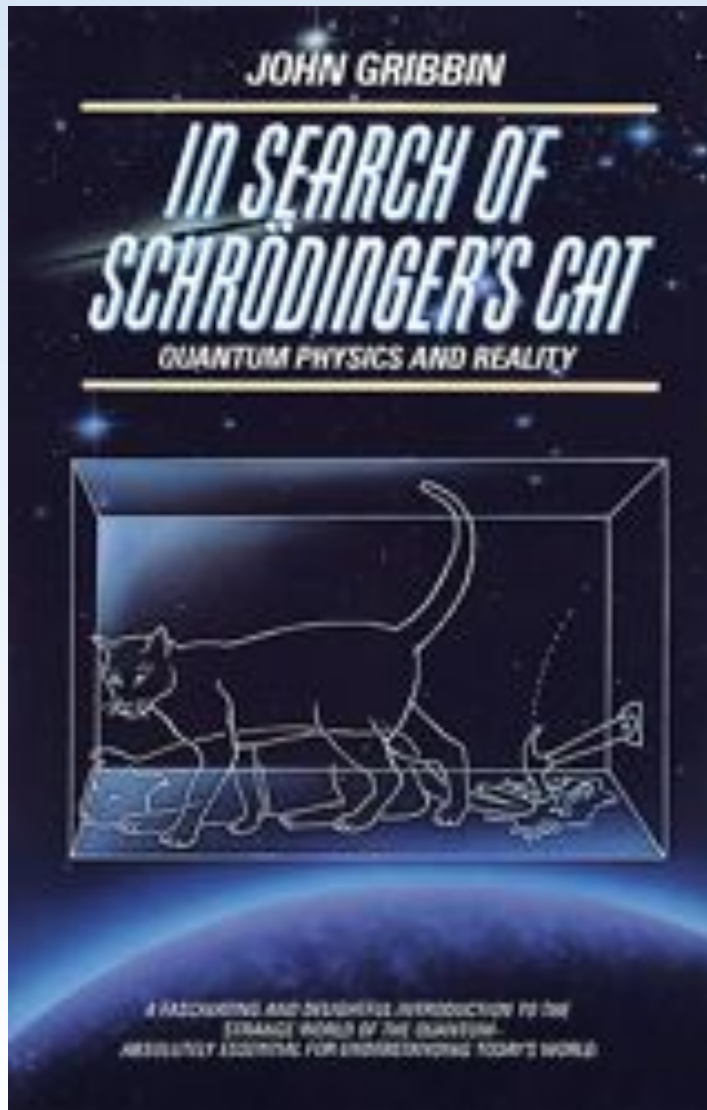
(NIST Boulder)



# Timeline of QM + Entanglement

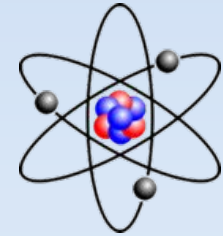


# A couple of good books

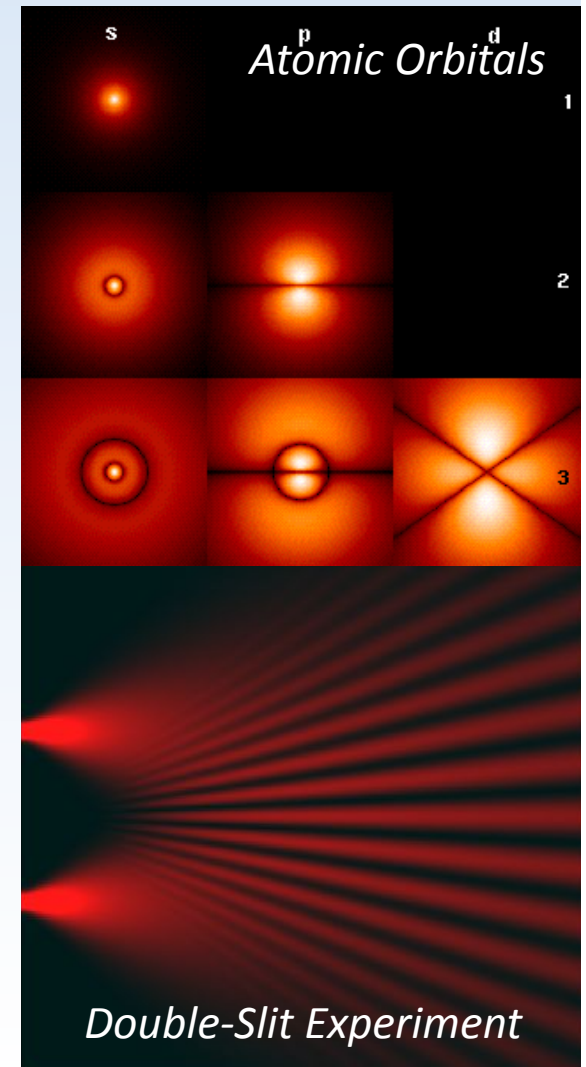


# $\Psi$

# Quantum Mechanics



- Invented to describe electrons, atoms, photons, and presumably the whole universe, based on **probability**
- **Uncertainty principle:** position and momentum cannot be measured simultaneously (*complementary properties*)
- **Superposition:** Particles can be in many states or places at once (*wave-particle duality*)
- Multiple Particles: **Entanglement**





# Entanglement

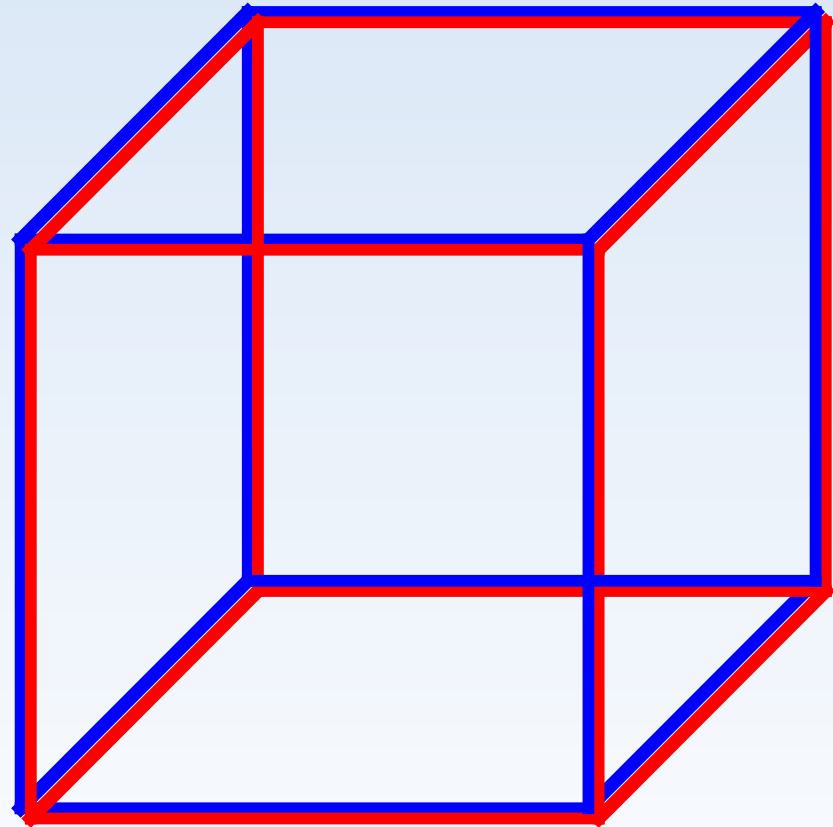


- “When two systems ... enter into temporary physical interaction ... then they can no longer be described ... [by states of their own]. I would not call that *one* but rather *the* characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought.
- ***By the interaction the two ... have become entangled.***

---Erwin Schrödinger, 1935

# Quantum Cube

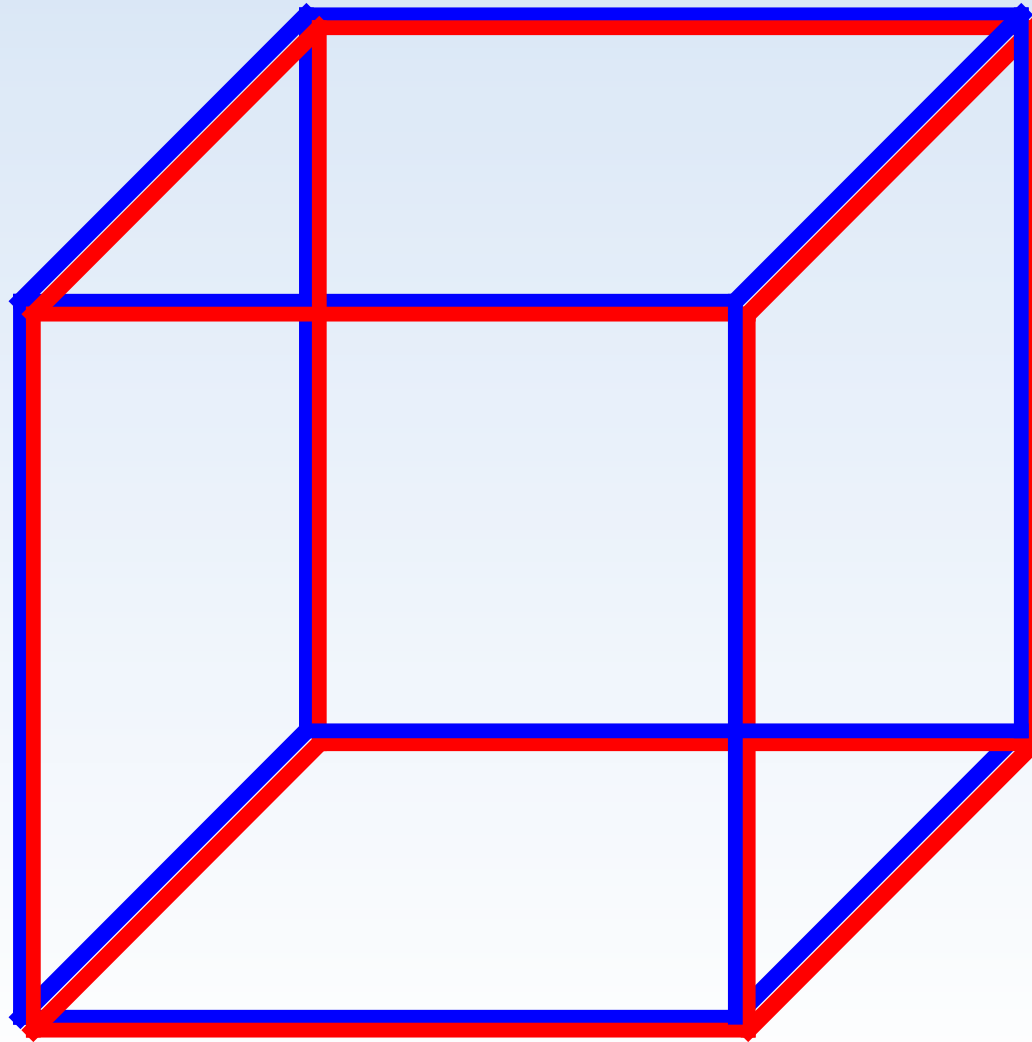
- Object with two ***complementary properties:***
- **Orientation**  
(Position)
- **Color**  
(Momentum)



Analogous to properties of an electron, atom, ...

Adapted from Fred Alan Wolf, *Taking the Quantum Leap* and *Parallel Universes*

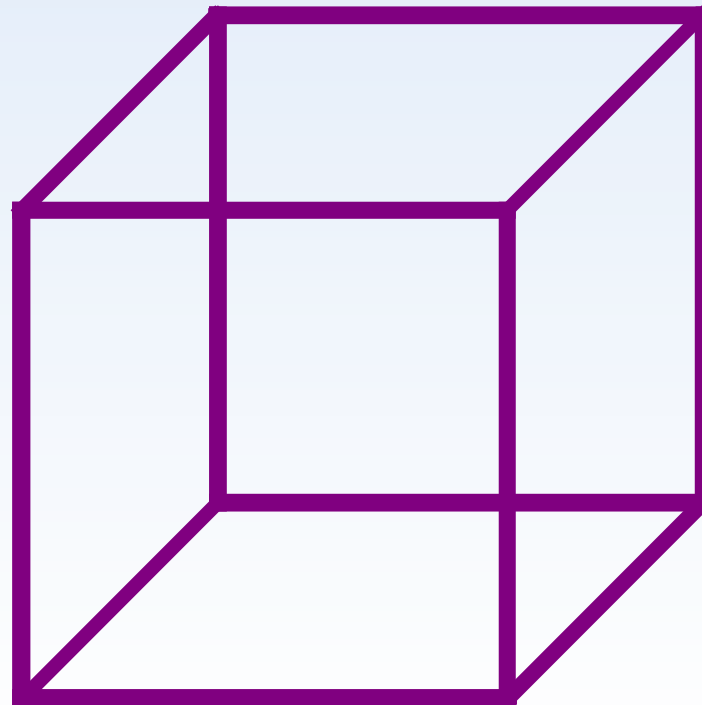
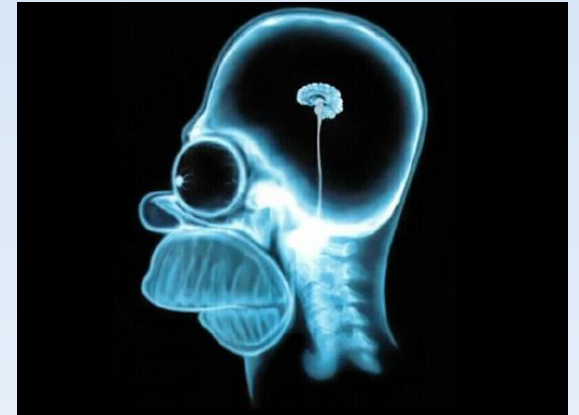
What is the orientation?





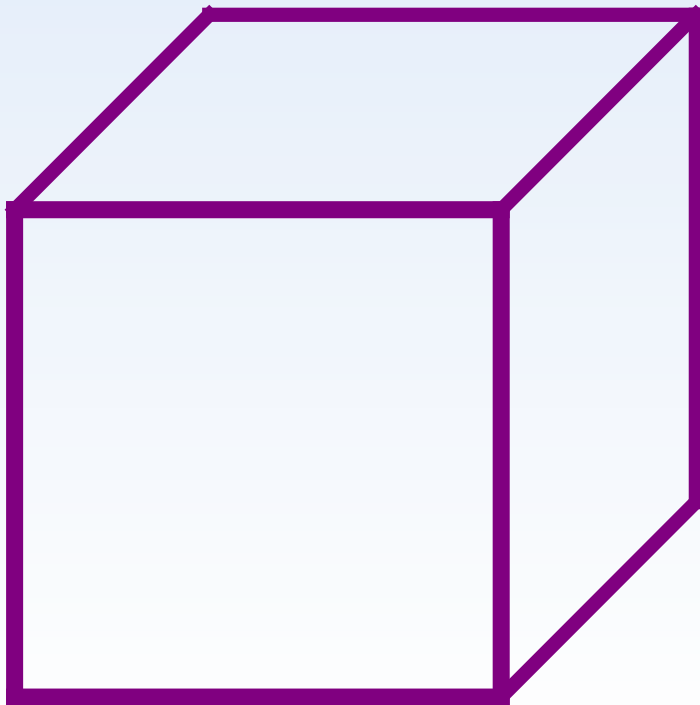
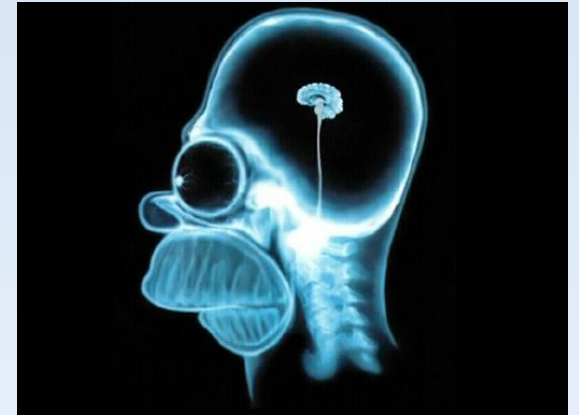
# Orientation

- Known as “Necker Cube”
- Ambiguous Perception

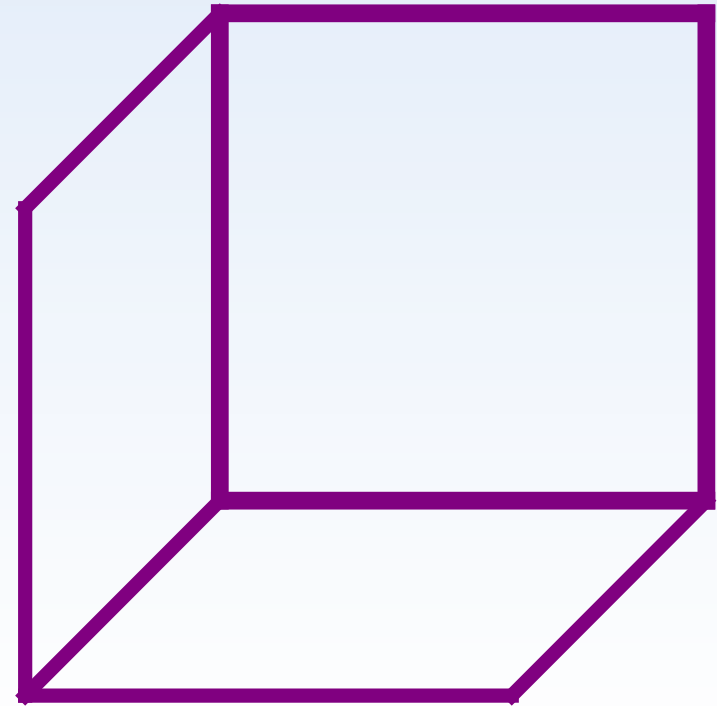


# Orientation

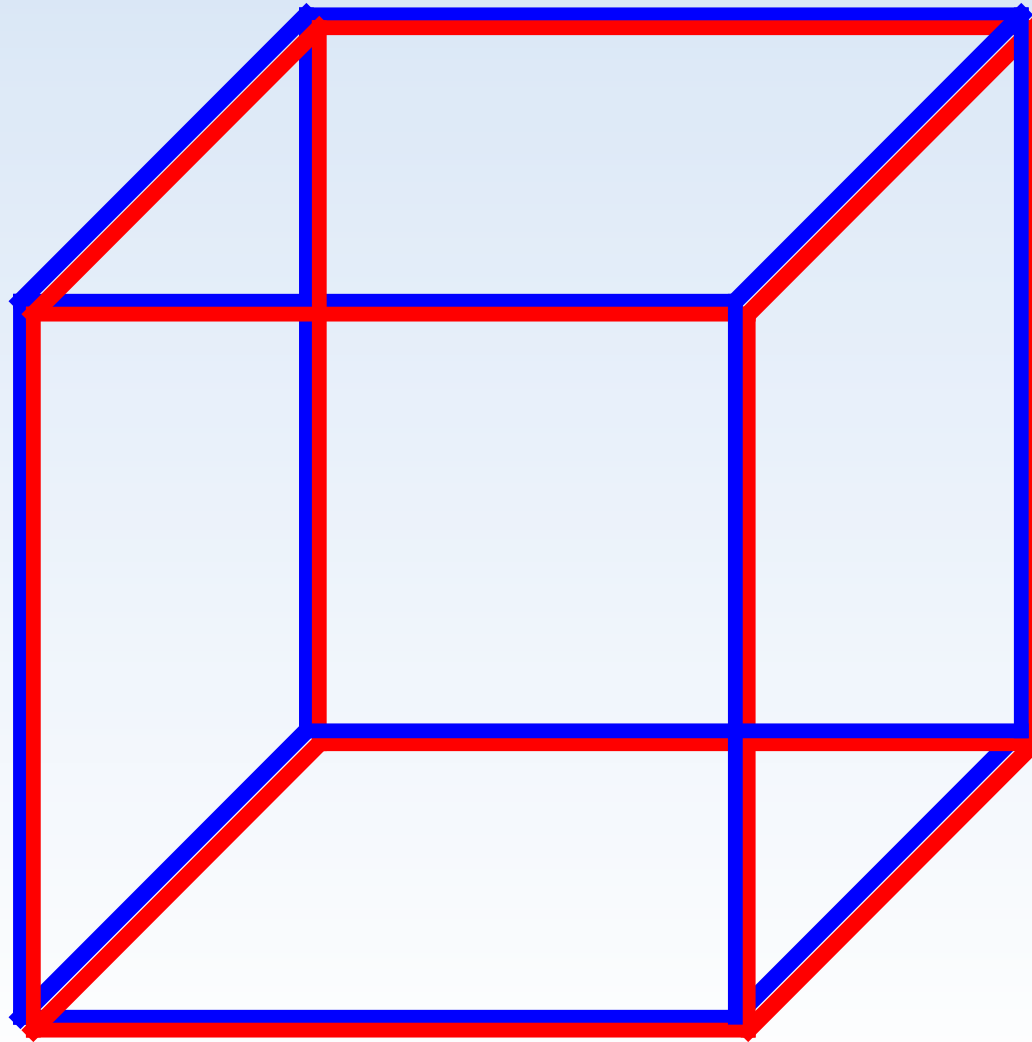
- Known as “Necker Cube”
- Ambiguous Perception



Points  
Up  
*and*  
Down

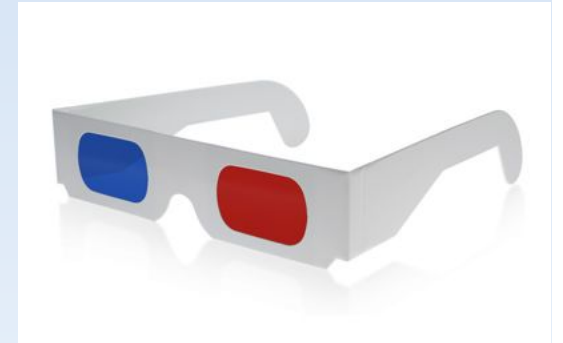
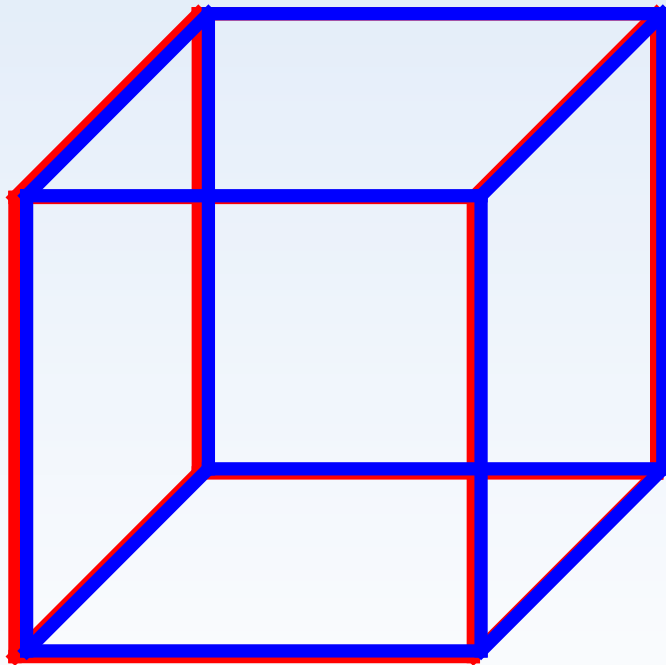


What is the color?



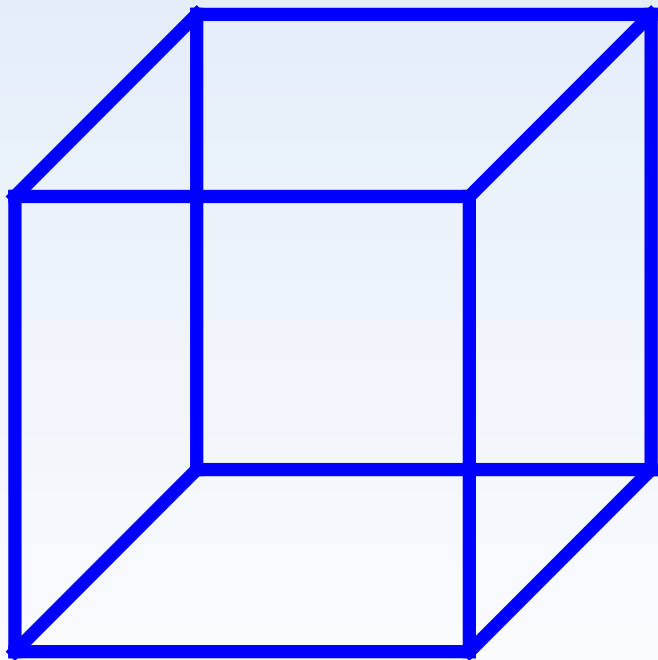
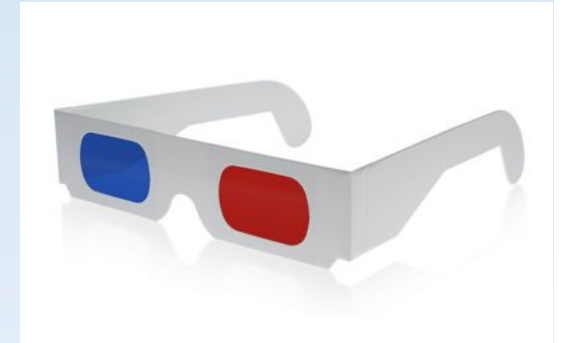
# Color

- Imagine we could only see Red or Blue

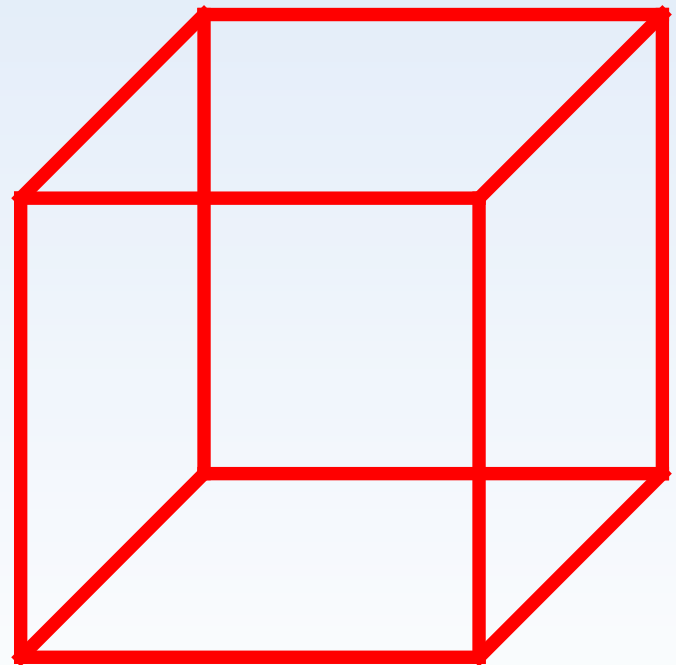


# Color

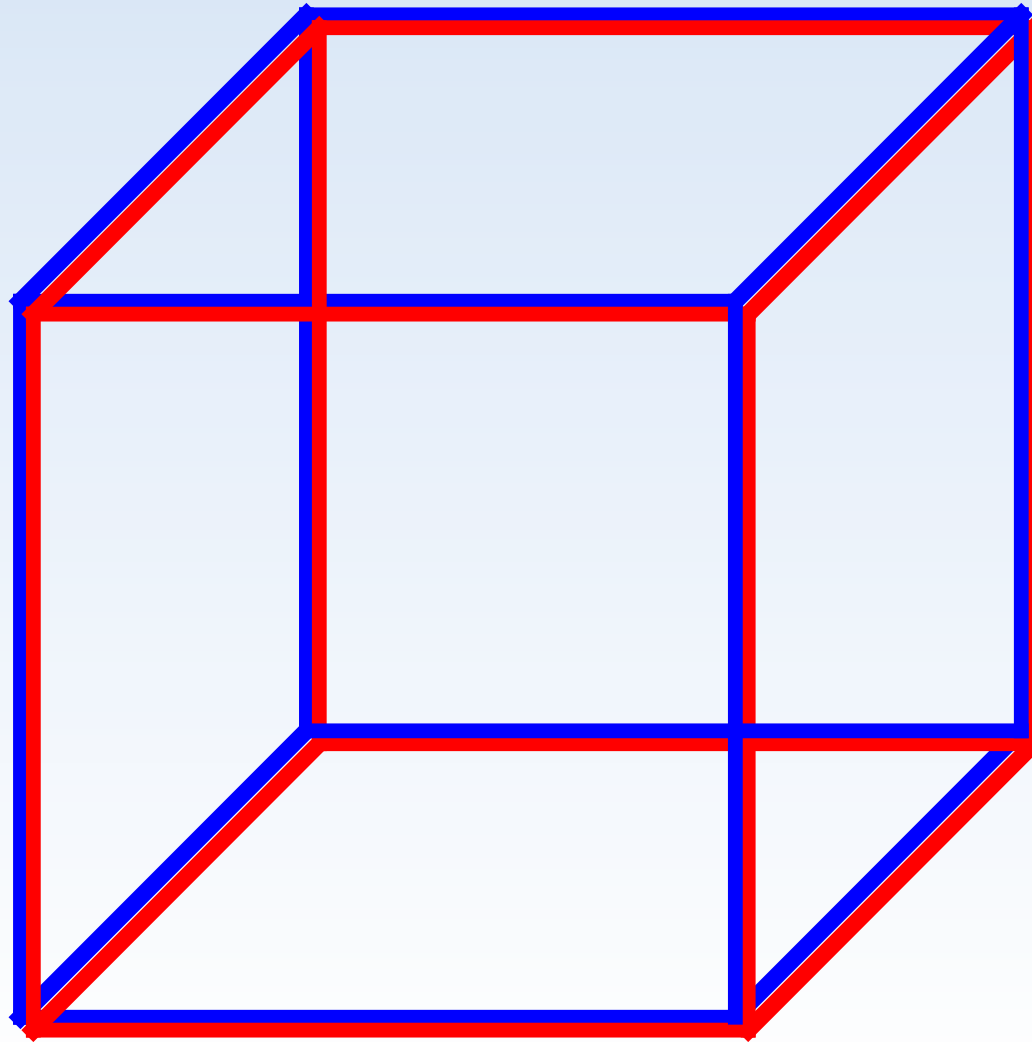
- Imagine we could only see Red or Blue



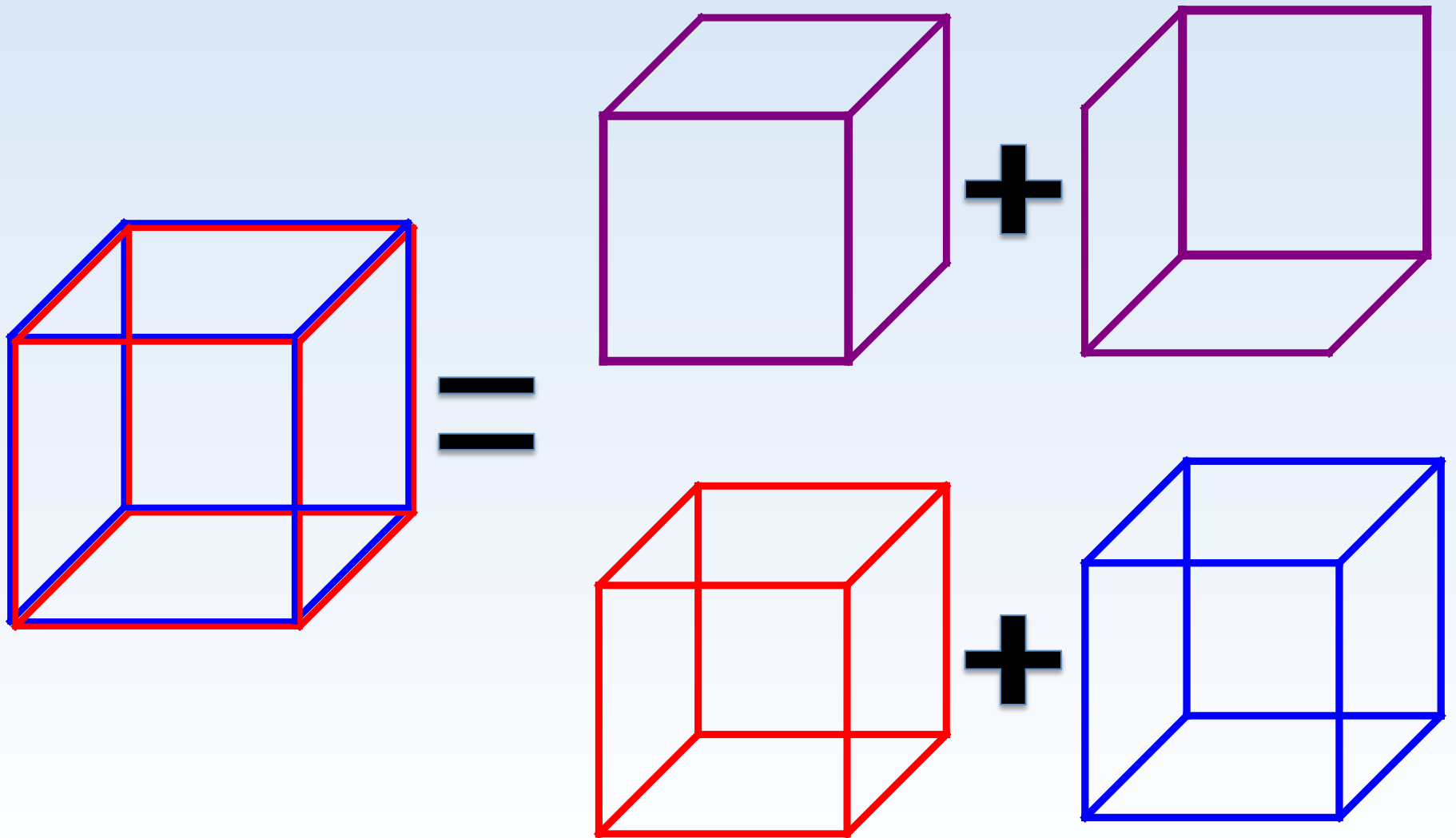
Colored  
Red  
*and*  
Blue



What is this cube?

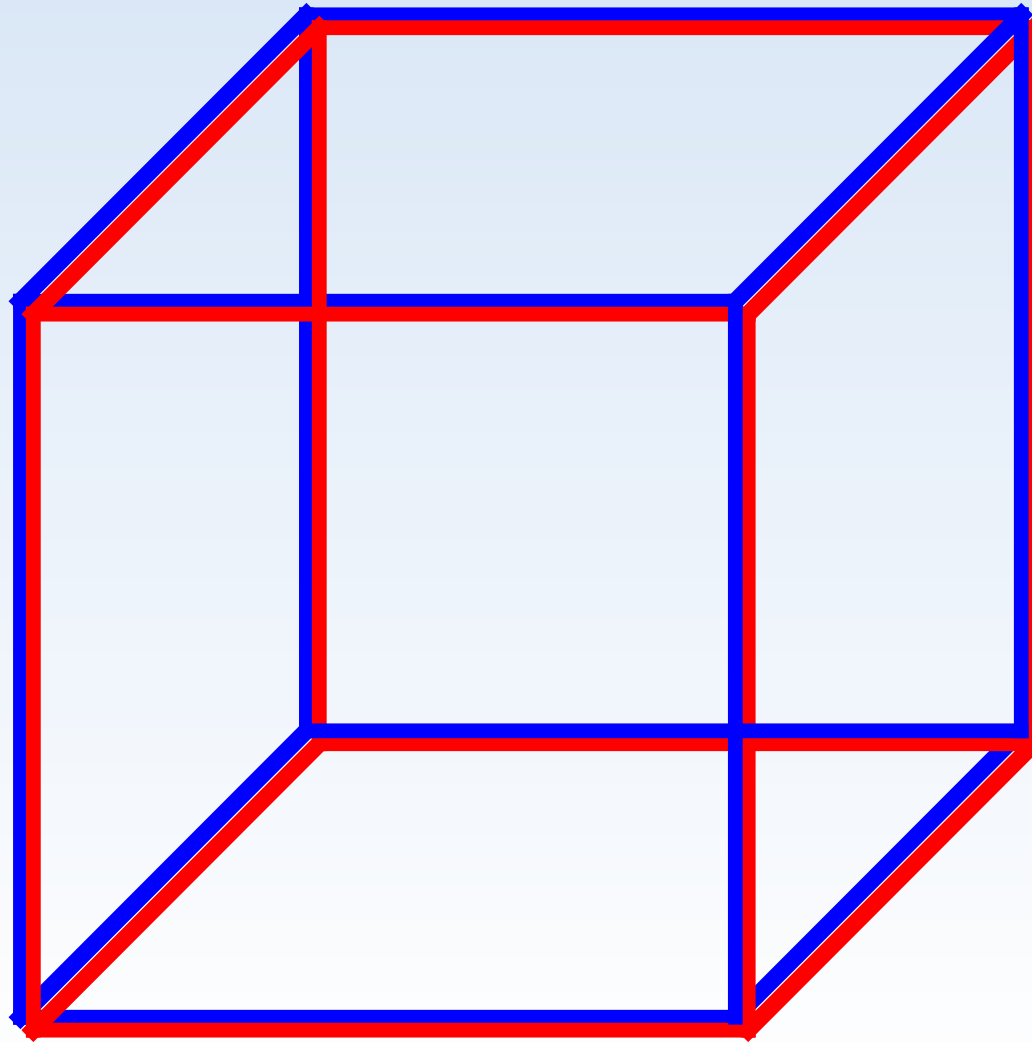


# Quantum Superposition





# But what is it really?



Analogy: What is an electron? Particle or Wave?

# Quantum Reality



- **Heisenberg** might say “It is impossible to determine accurately *both* the position and momentum of an electron simultaneously.”



- **Bohr** might further say “one cannot ascribe a pre-existing reality to position and momentum before measurement.”

# Quantum Reality



- **Heisenberg** might say “It is impossible to determine accurately *both* the orientation and color of a cube simultaneously.”



- **Bohr** might further say “one cannot ascribe a pre-existing reality to orientation and color before measurement.”

**Qubit** = Quantum bit  
= binary digit

- Many systems in nature are only found in two quantum states:
- Photon polarization (horizontal or vertical)
- Electron or Nuclear Spin (*up or down*)
- Ions, Atoms, or Superconductors (zero or one quanta of energy)

$$|\Psi\rangle = a|0\rangle + b|1\rangle$$

Quantum State

=

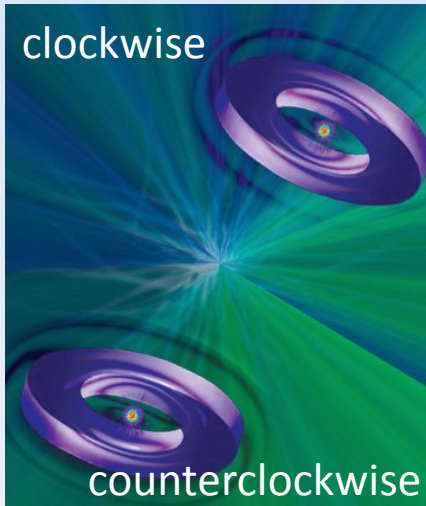
Superposition of Two  
Distinct Possibilities

Cube-bit

$$|\text{cube}\rangle = |\text{cube}\rangle + |\text{cube}\rangle$$

**Qubit** = Quantum bit

= binary digit



exists in nature  
and in two  
states:  
polarization  
(horizontal or vertical)

- Electron or Nuclear Spin (*up or down*)
- Ions, Atoms, or Superconductors (zero or one quanta of energy)

$$|\Psi\rangle = a|0\rangle + b|1\rangle$$

Quantum State

=

Superposition of Two  
Distinct Possibilities

Cube-bit

$$|\text{cube}\rangle = |\text{cube}\rangle + |\text{cube}\rangle$$

# EPR



A. Einstein



B. Podolsky



N. Rosen

MAY 15, 1935

PHYSICAL REVIEW

VOLUME 41

## Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

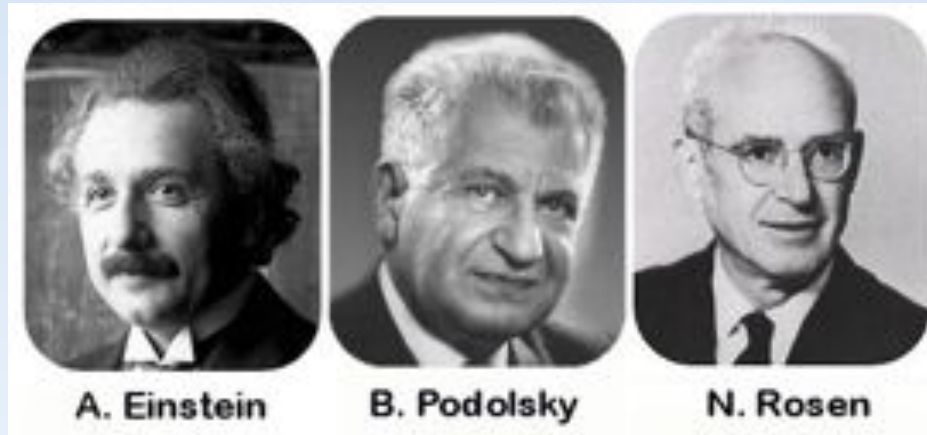
A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function is

quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.

# EPR

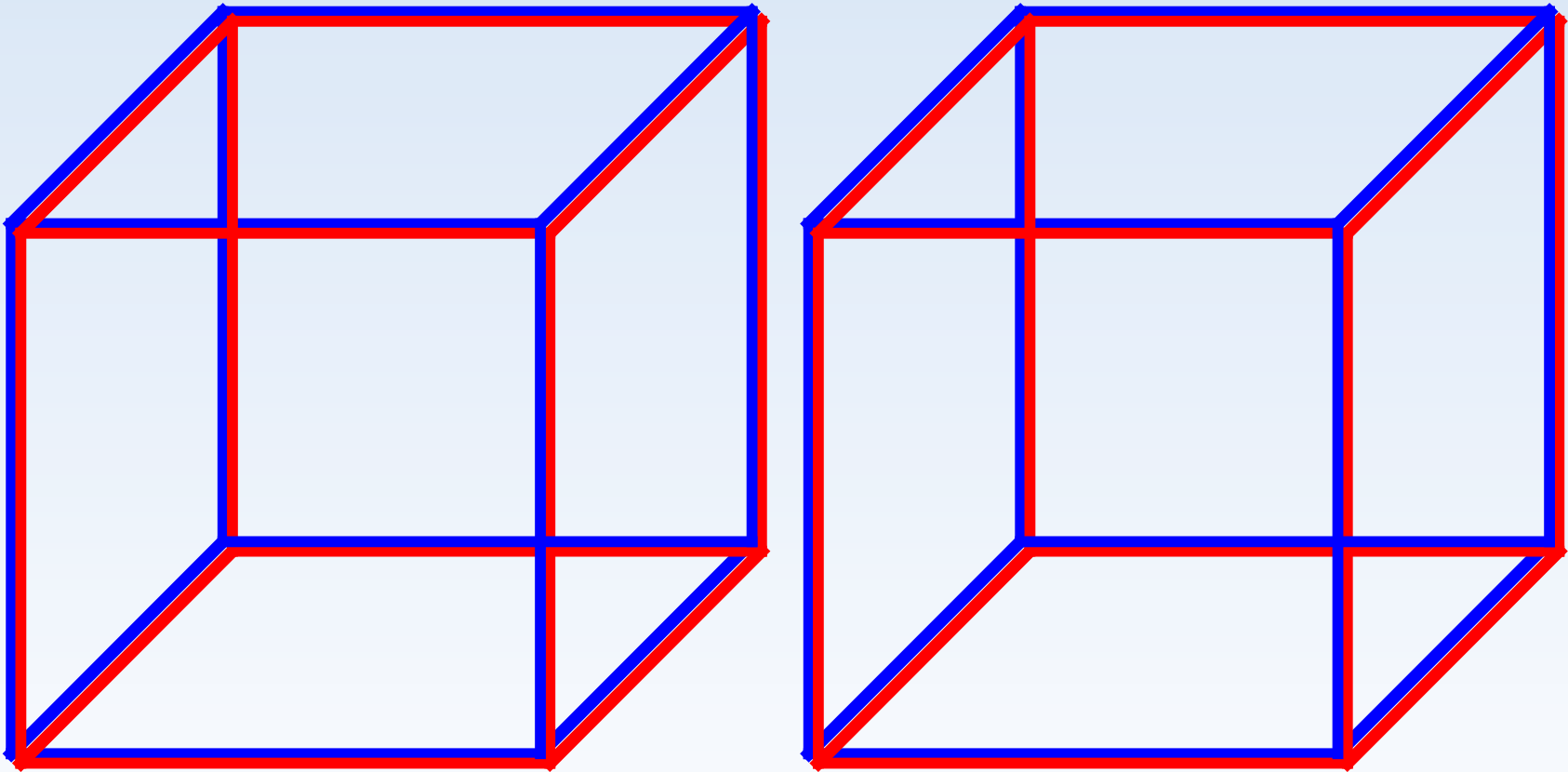


## ***Brilliant attack on QM & Reality***

- “If, without in any way disturbing a system, we can **predict with certainty** (i.e., with probability equal to unity) the value of a physical quantity, then there exists an **element of reality** corresponding to that quantity.”
- QM forbids such *reality* for complementary properties
- EPR “demonstrate” *reality* for two *entangled* particles

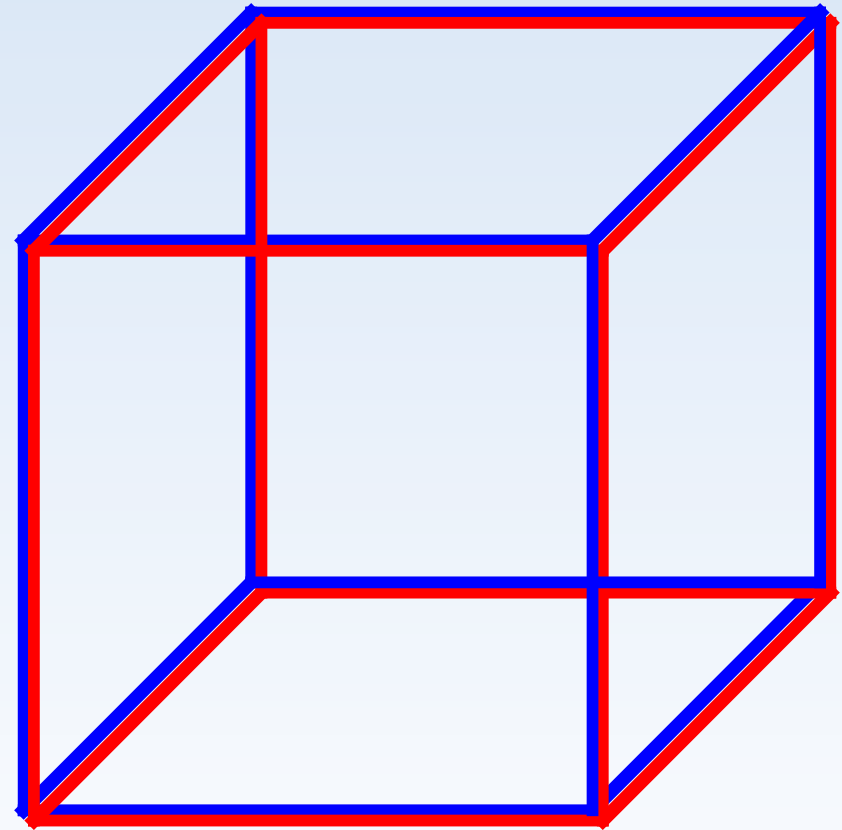
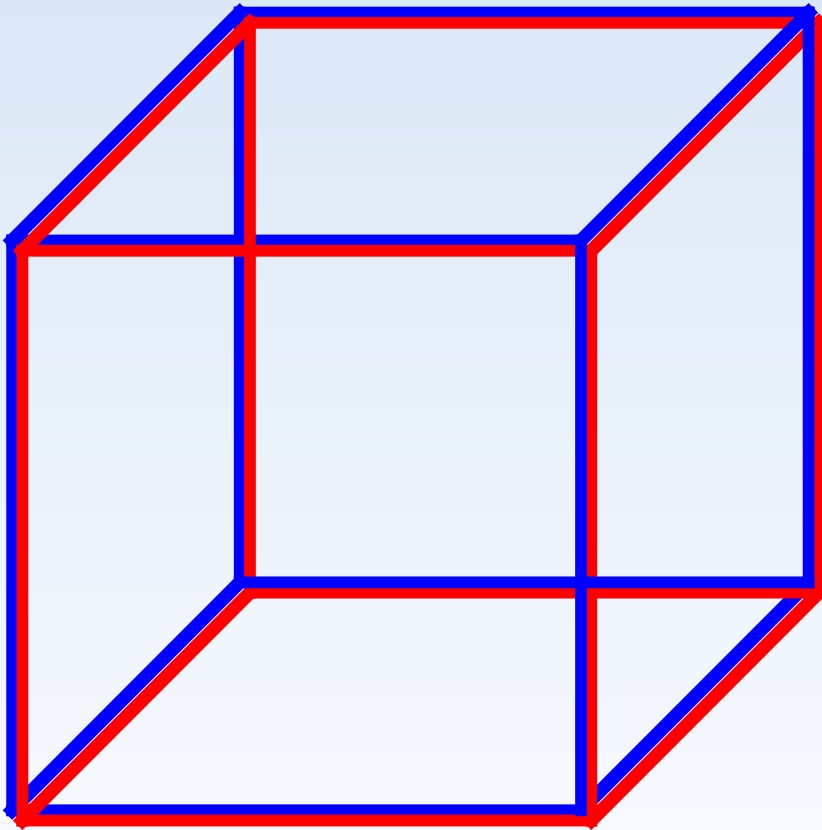
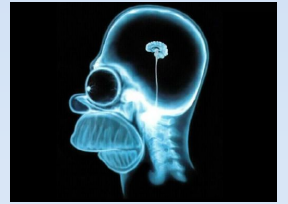


# Entangled Cubes

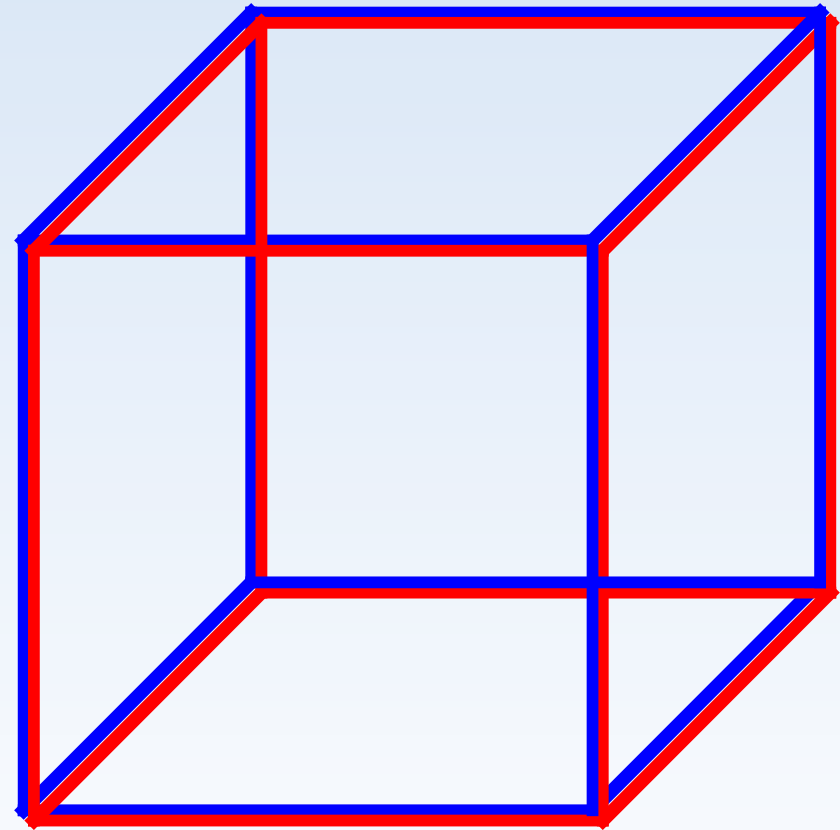
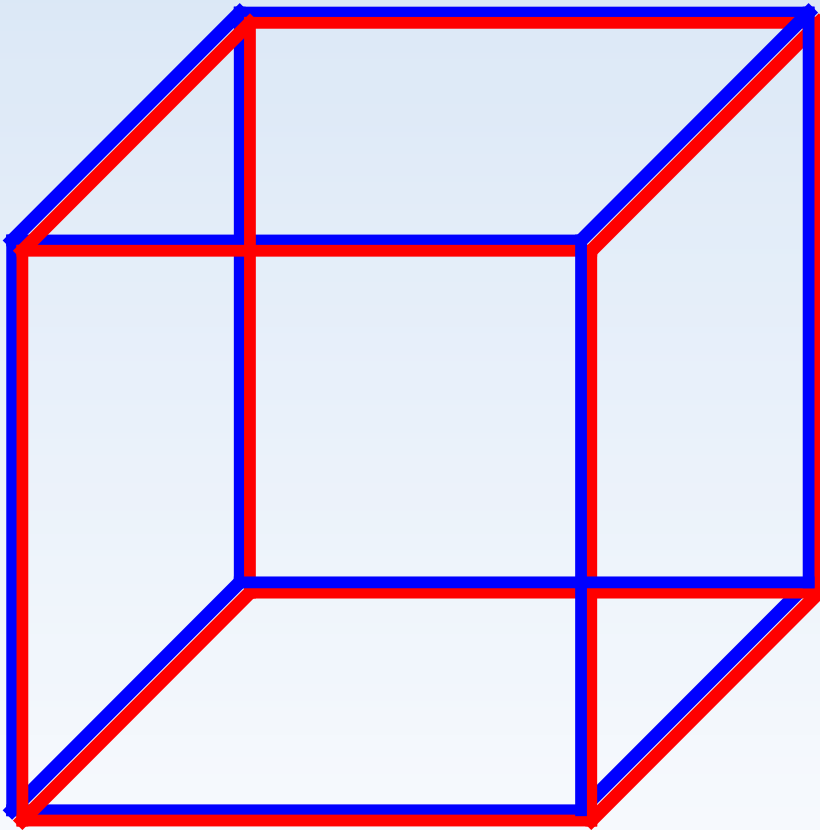
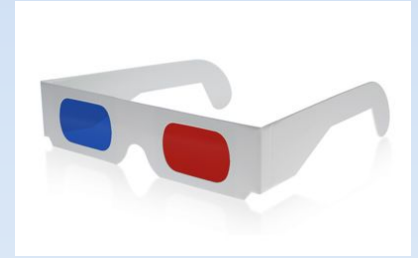


Adapted from Fred Alan Wolf, *Taking the Quantum Leap* and *Parallel Universes*

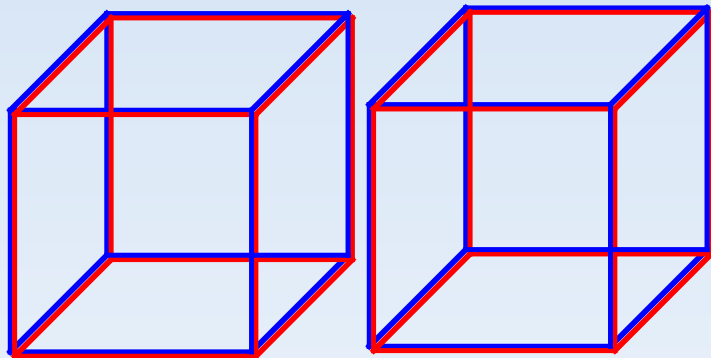
# What are the orientations?



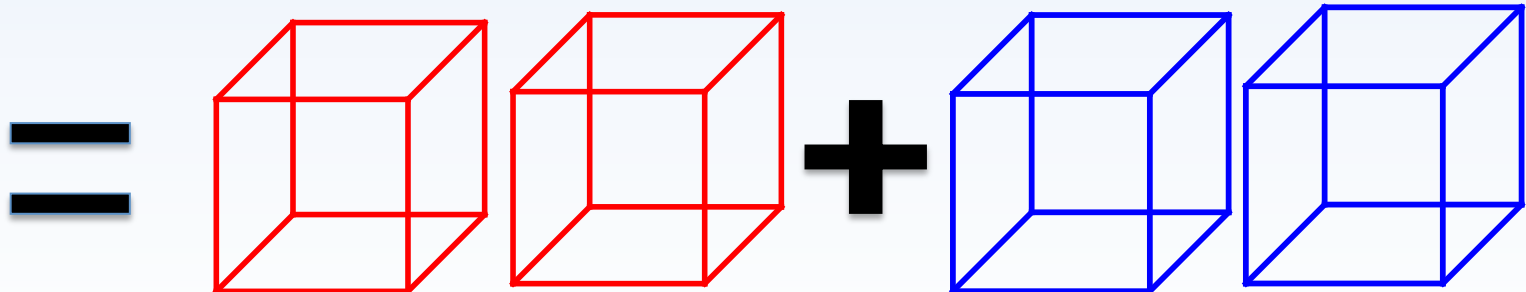
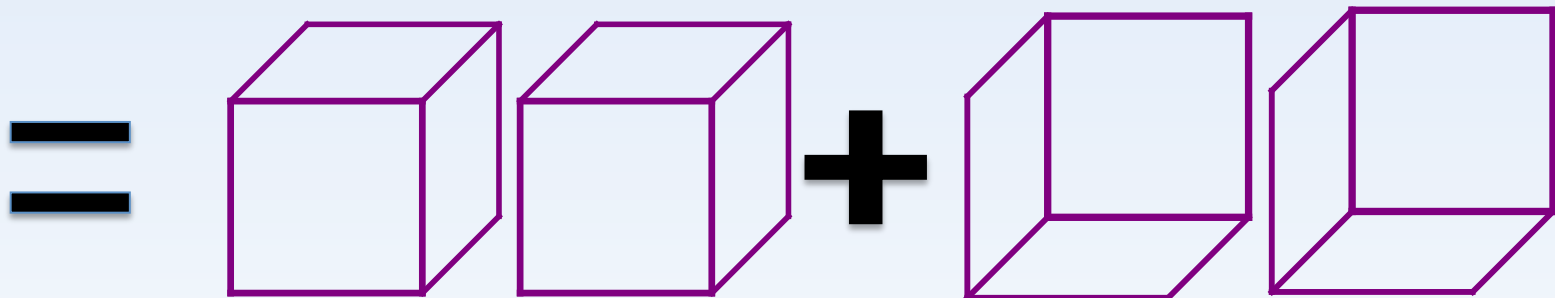
What are the colors?



# EPR: Spooky correlations

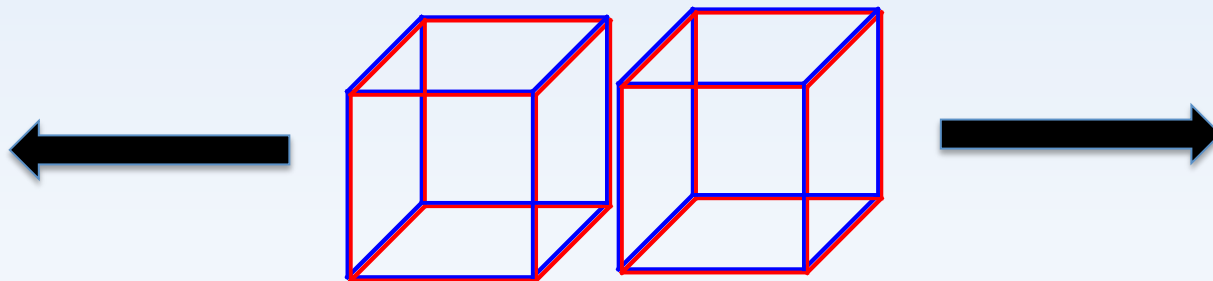


Correlated orientations + colors!



# EPR argument

- Take quantum cubes to opposite ends of the Earth, measure the left cube's **color**:



# EPR argument

- Take quantum cubes to opposite ends of the Earth, measure the left cube's **color**:



# EPR argument

- Whatever the outcome, QM predicts that the right cube will have the *same color*.





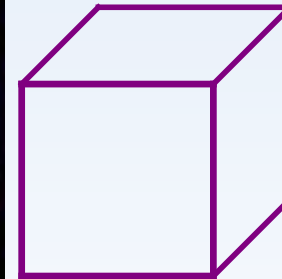
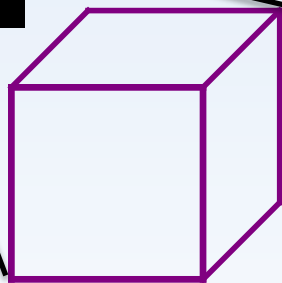
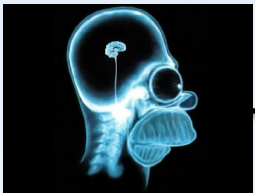
# EPR argument

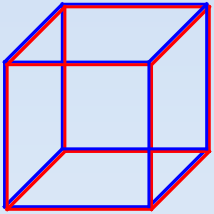
- Or... measure the left cube's **orientation**:



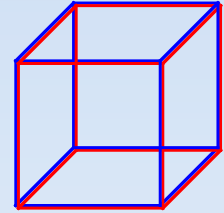
# EPR argument

- Whatever the outcome, we can be certain the right cube will have the ***same orientation***.





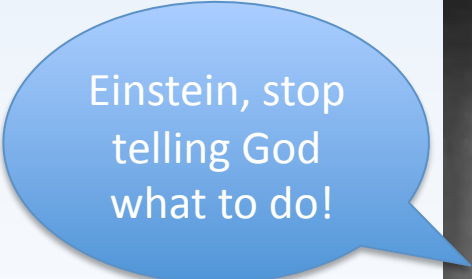
# Quantum Reality



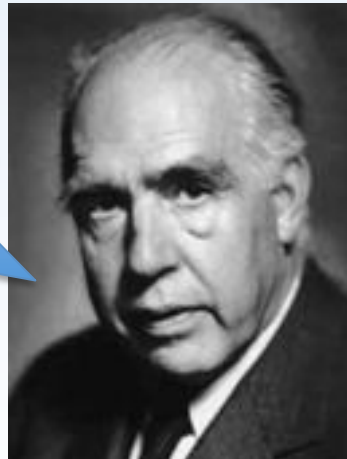
- By looking at one cube, we can predict, *with certainty*, either the color or orientation of the other cube, thus *both are real*.

- ***EPR argument***

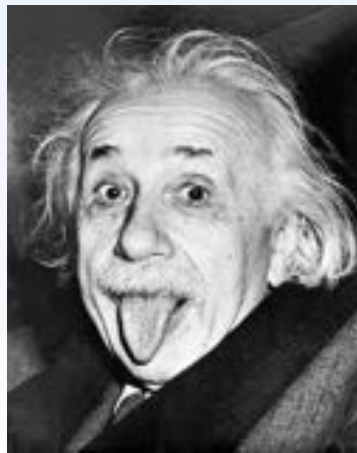
*QM forbids such certainty, thus **QM is incomplete***



Einstein, stop  
telling God  
what to do!



**Bohr**

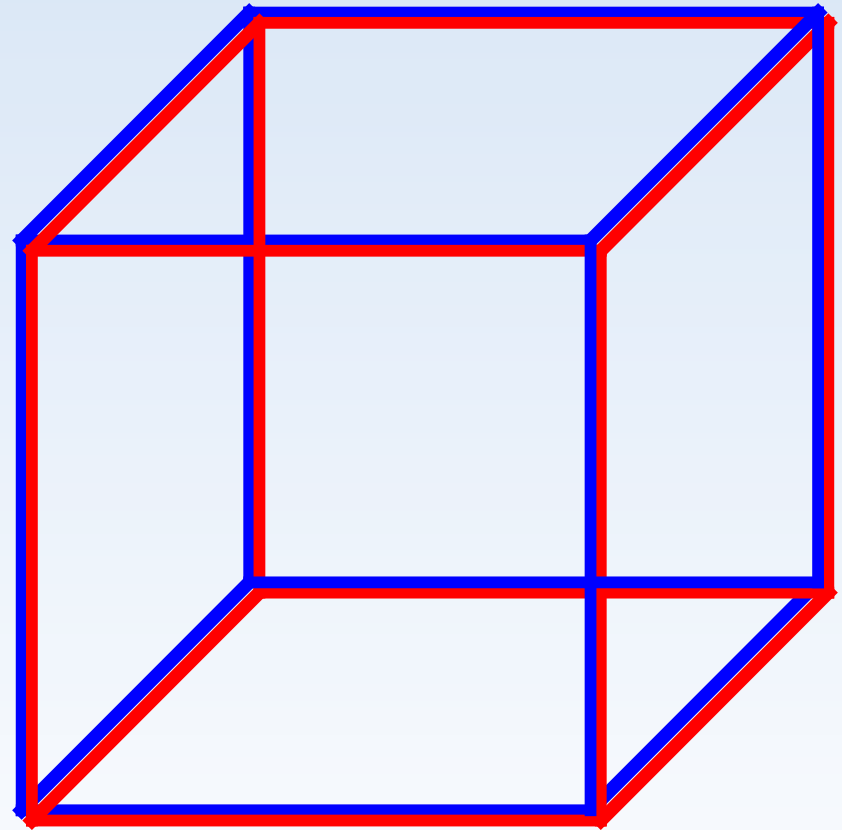
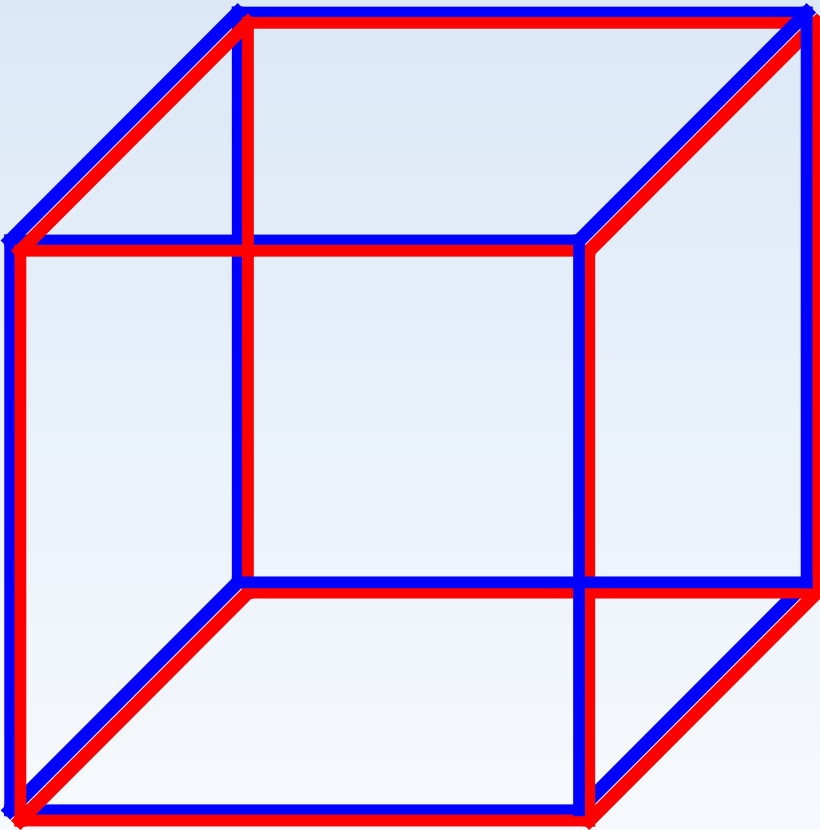


**Einstein**

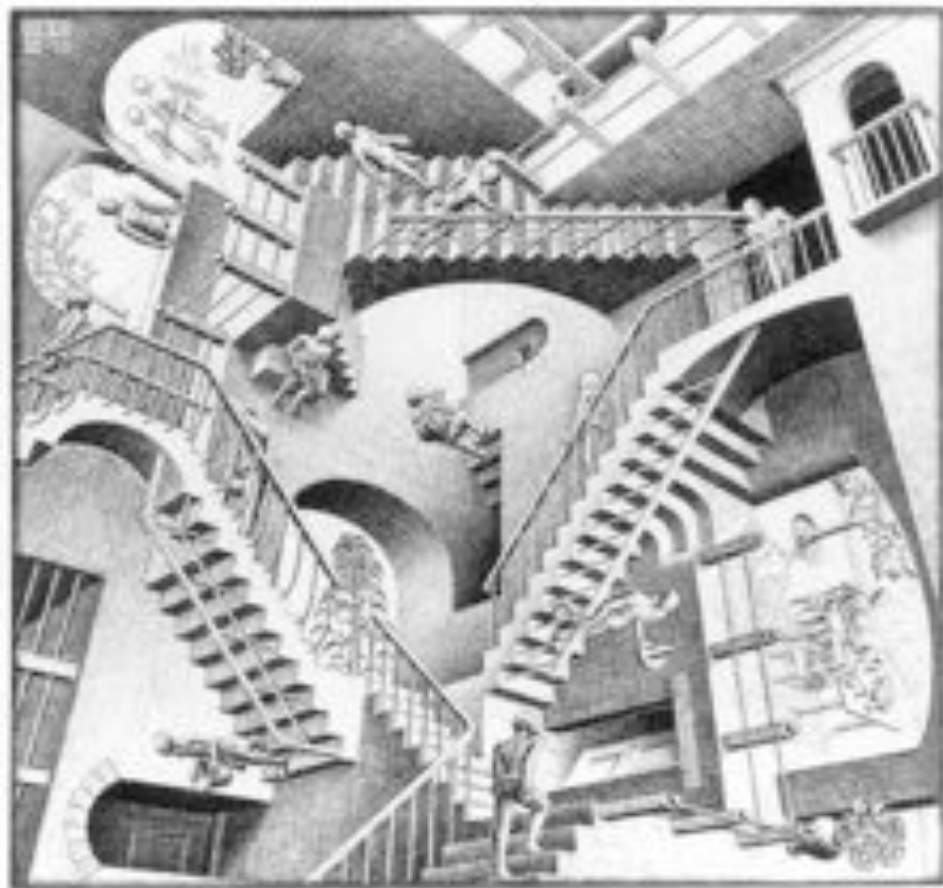


God does not  
play dice  
with the  
universe!

# Interlude



# Art of Impossibility

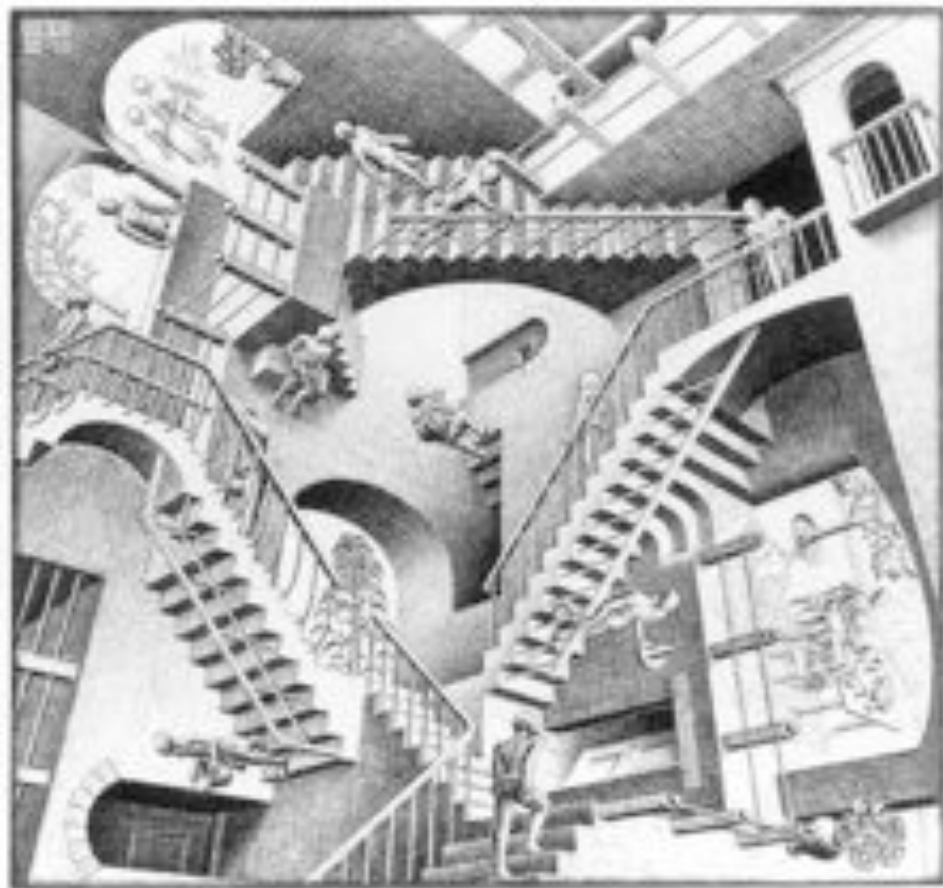


M. C. Escher





# Art of Impossibility



M. C. Escher



# Entangled Qubits

- Two qubits (A and B) are entangled if their quantum state is **not** of the form

$$(a|0\rangle + b|1\rangle)_A (c|0\rangle + d|1\rangle)_B$$

- An **EPR pair** has the entangled state

$$|0\rangle_A |0\rangle_B + |1\rangle_A |1\rangle_B$$

- Neither A nor B have a definite state of their own, but there is a definite correlation!



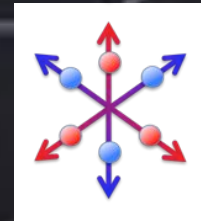
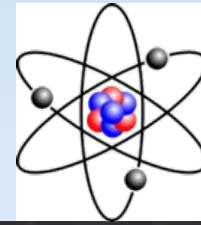
# Entanglement



$$\boxed{|0\rangle_A |0\rangle_B + |1\rangle_A |1\rangle_B}$$

- “Another way of ... [understanding entanglement] is: the best possible knowledge of a whole does not necessarily include the best possible knowledge of all its parts, even though they may be entirely separate”

# Schrödinger's cat

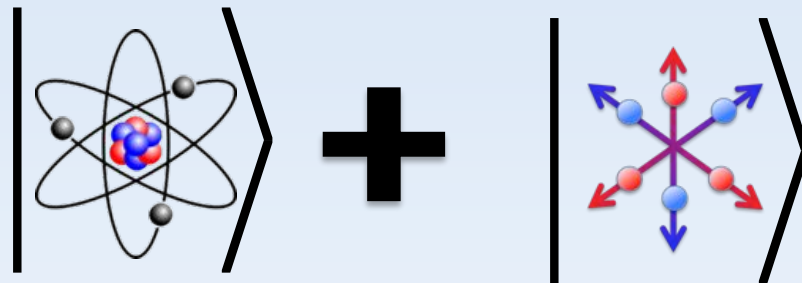


From John Gribbin, *In Search of Schrödinger's Cat*

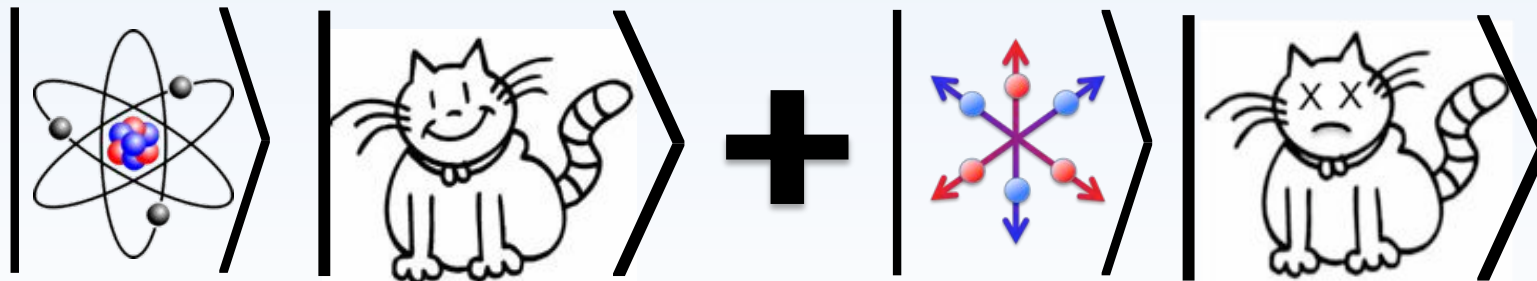
# Schrödinger's quantum cat



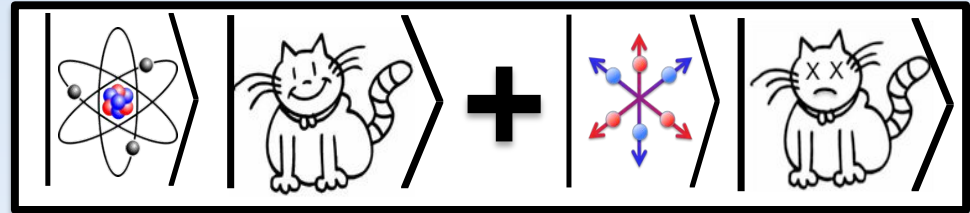
Atom in **superposition**



By the interaction, they have become **entangled**

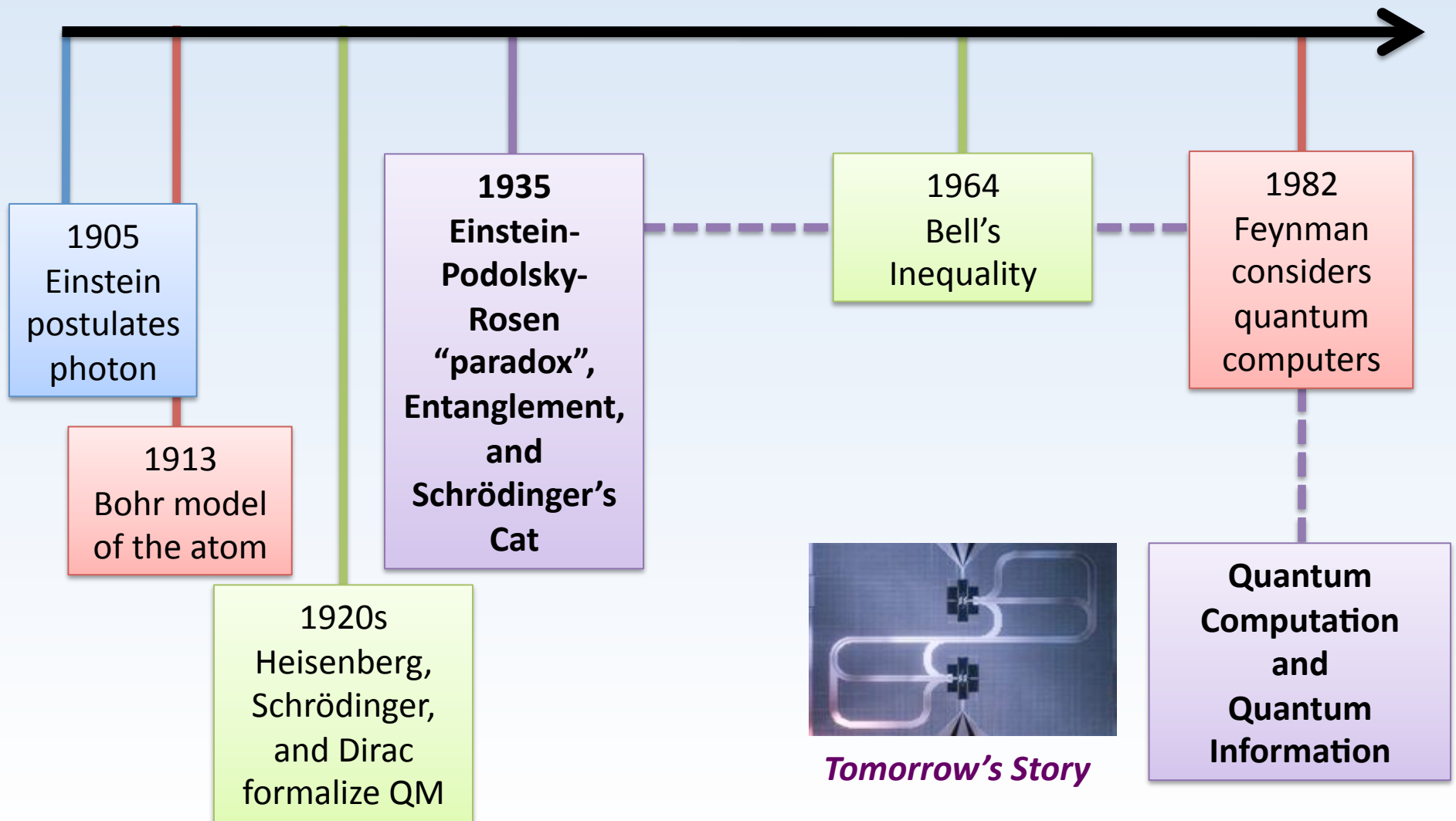


# Schrödinger's cat paradox



- “...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. ...
- ***There is a difference between a shaky or out-of-focus photograph and a snapshot of clouds and fog banks.***”

# Timeline of QM + Entanglement



# Applications of Entanglement

- **Quantum Teleportation:** Communicate quantum states by shared entanglement
- **Quantum Cryptography:** Communicate securely using the laws of physics
- **Quantum Computing:** Perform superfast calculations in superposition
- **Experimental Metaphysics:** Test the “elements of reality”

# Teleportation

- Discovered by Bennett, Brassard, Crepeau, Jozsa, Peres, and **Wootters**
- Useful for quantum computers!



Very Unlikely



but who knows?



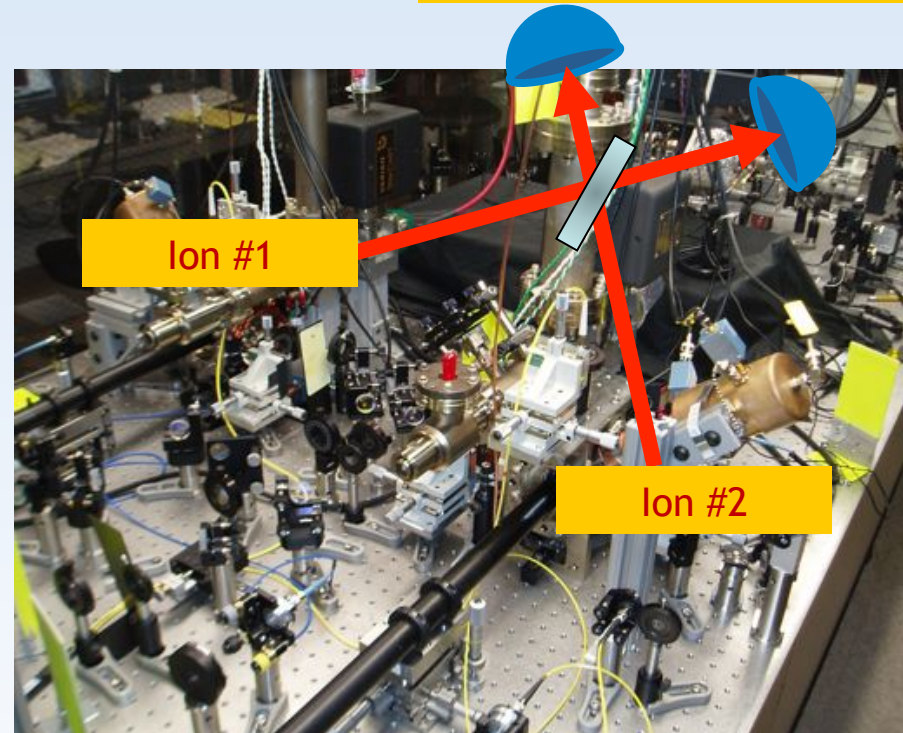
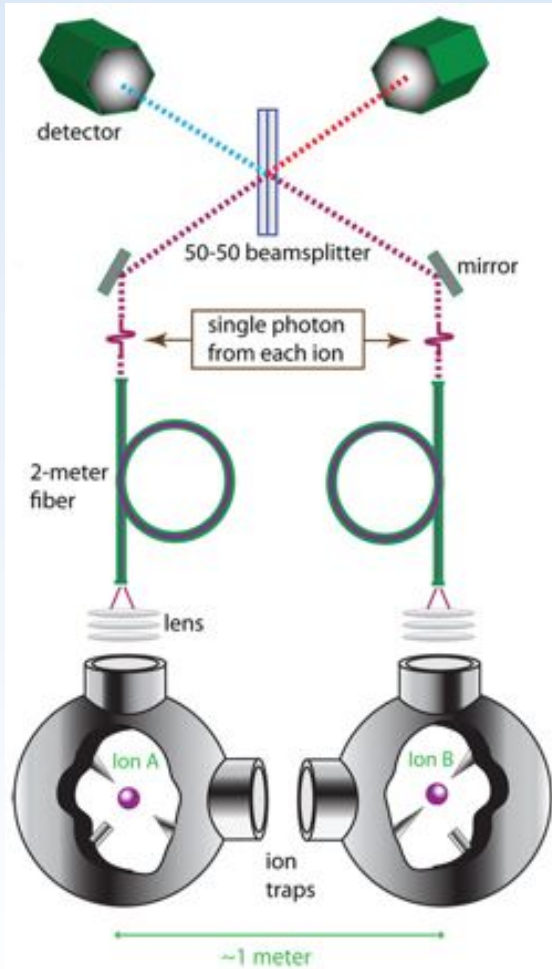


# Teleportation

- Chris Monroe @ UMD/JQI

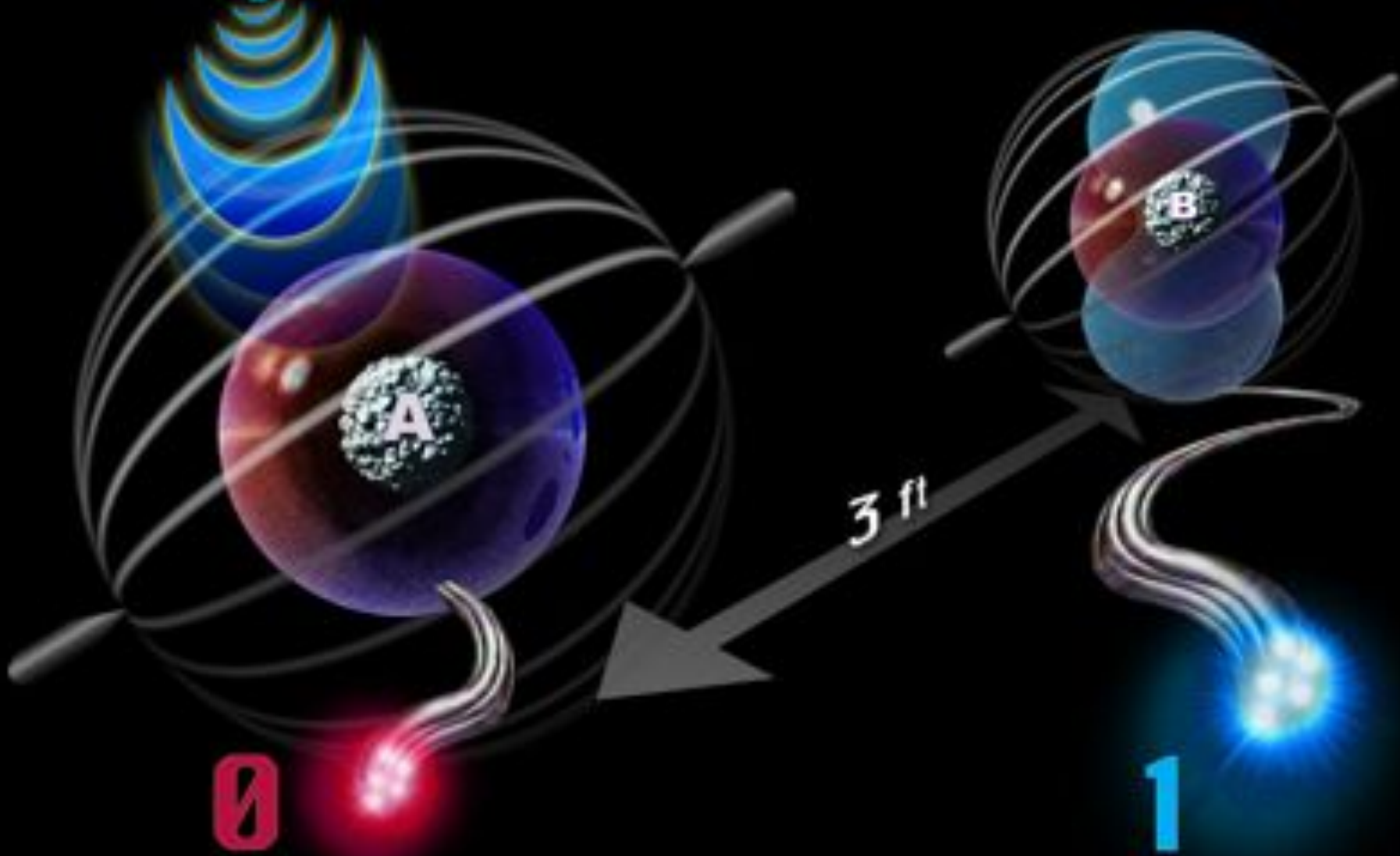
Detect coincident event:

$$\alpha|\downarrow\rangle|\uparrow\rangle - \beta|\uparrow\rangle|\downarrow\rangle$$





11010010101111

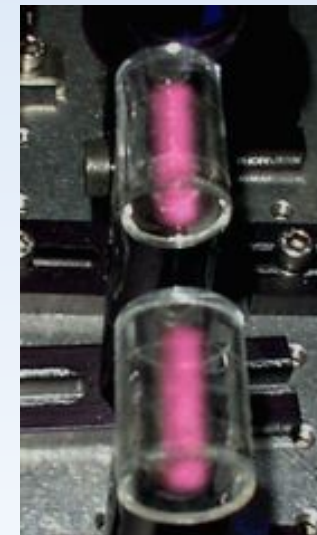
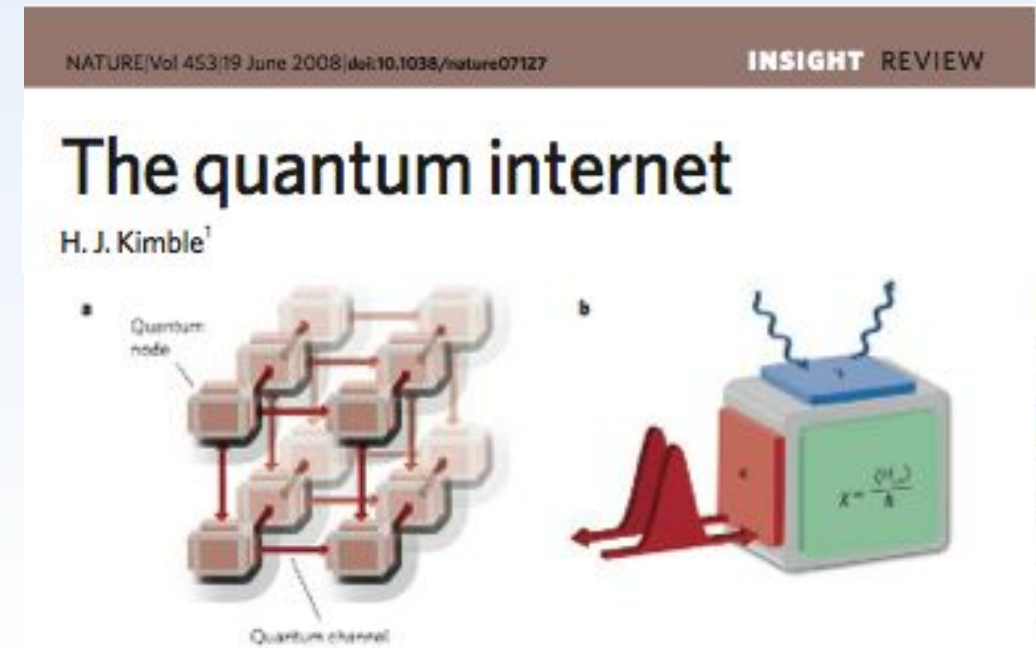


~1 meter

# Quantum Cryptography

Small-scale units in use

Large-scale units require quantum repeaters



**letters to nature** 2001

**Experimental long-lived entanglement of two macroscopic objects**

Brian Julsgaard, Alexander Kozhekin & Eugene S. Polzik

*Institute of Physics and Astronomy, University of Aarhus, 8000 Aarhus, Denmark*

# Quantum Computing

- Future devices that can harness entanglement to store and process information in parallel (*quantum parallelism*)

$$Q: \quad |input_1\rangle + |input_2\rangle + \dots$$



$$A: \quad |input_1\rangle|output_1\rangle + |input_2\rangle|output_2\rangle + \dots$$



# Experimental Metaphysics

- Bell's Inequality:

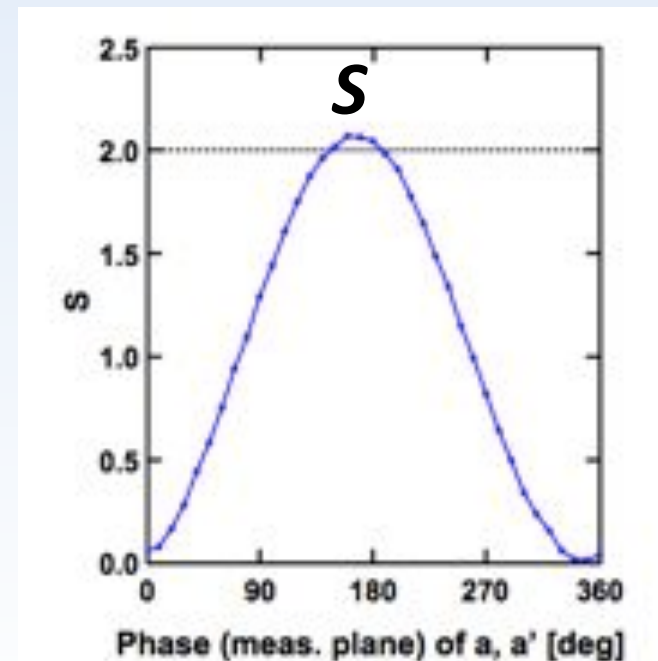
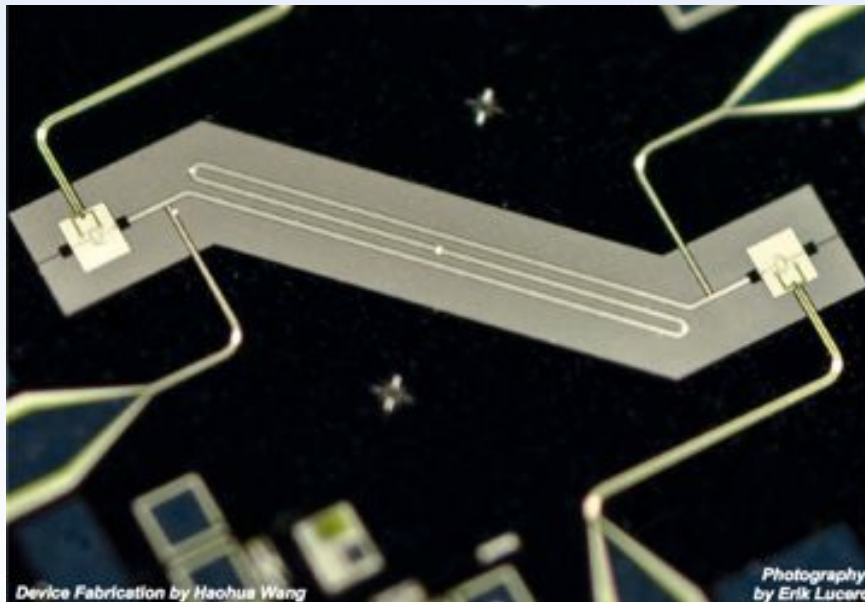
- $$S = \left| \langle (a + a')b + (a - a')b' \rangle \right| < 2$$

- All theories with ***local realism*** must obey this (with measurements of  $a, a', b, b' = \pm 1$ ), by simple arithmetic!
- Quantum theory's "arithmetic" is not simple  
**Entangled states have**

$$S_{QM} = 2\sqrt{2} = 2.828\dots$$

# Experiments on Metaphysics

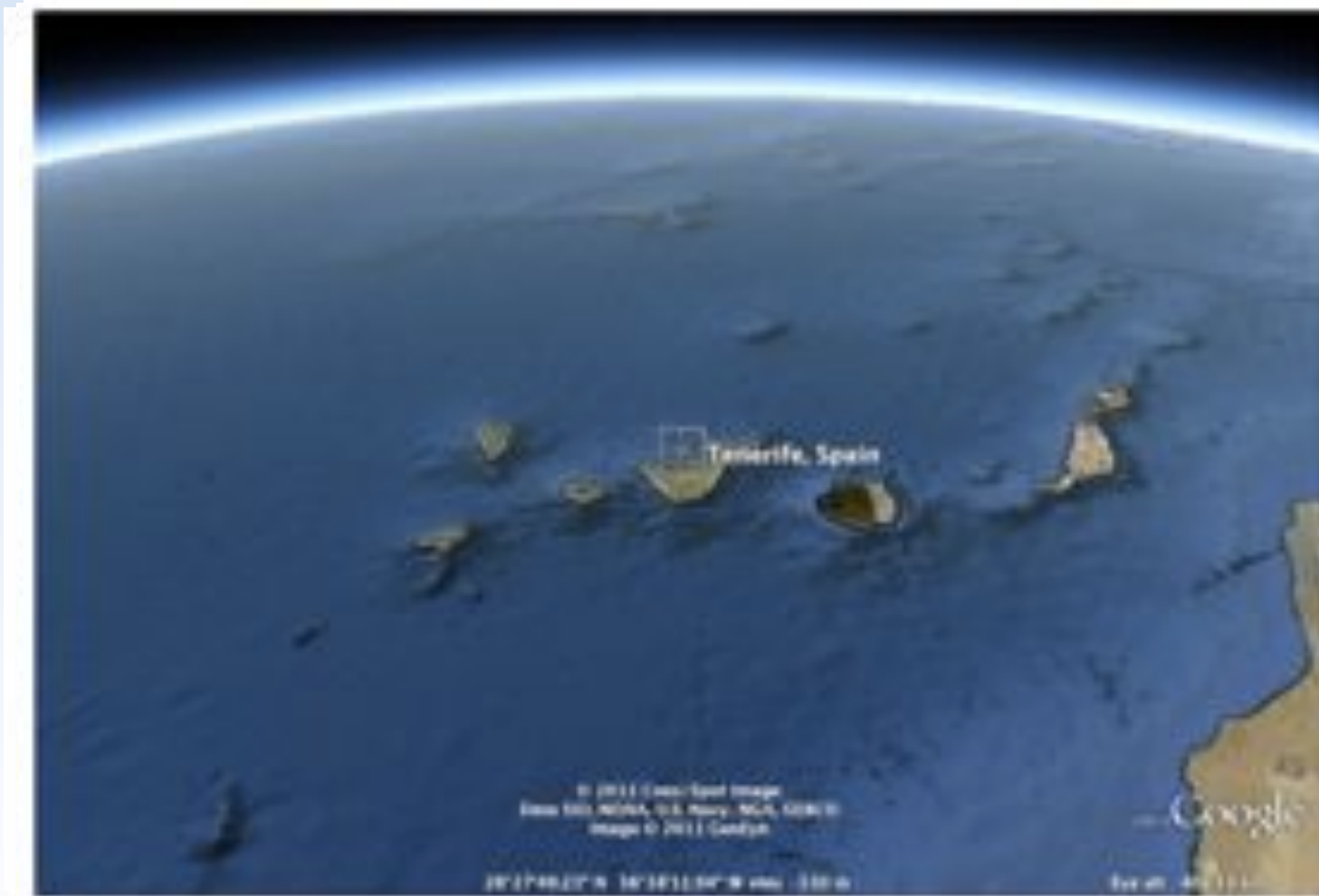
- A. Aspect (1982) performed celebrated **Bell Inequality** experiment using photons
- Repeated by many groups using photons, ions, and now superconductors (JM Martinis, UCSB) !



***NEXT TALK!***



# Bell/EPR realized



# Bell/EPR Realized

$$|\Psi\rangle = \frac{1}{\sqrt{2}} (|H\rangle_A |V\rangle_B - |V\rangle_A |H\rangle_B)$$

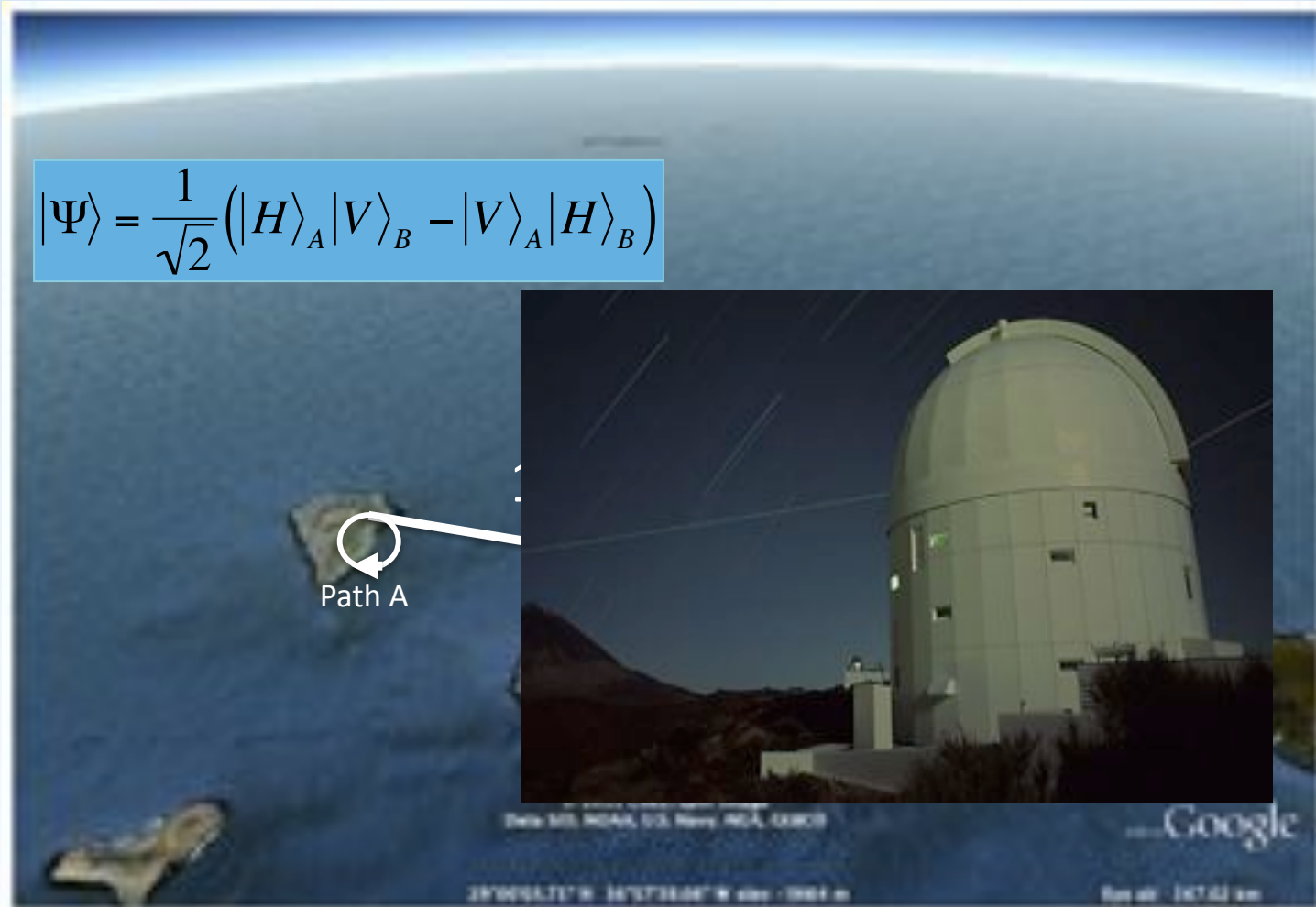


H = horizontally polarized photon  
V = vertically polarized photon

~90 miles

# Bell/EPR Realized

$$|\Psi\rangle = \frac{1}{\sqrt{2}} (|H\rangle_A |V\rangle_B - |V\rangle_A |H\rangle_B)$$



H = horizontally polarized photon  
V = vertically polarized photon

~90 miles

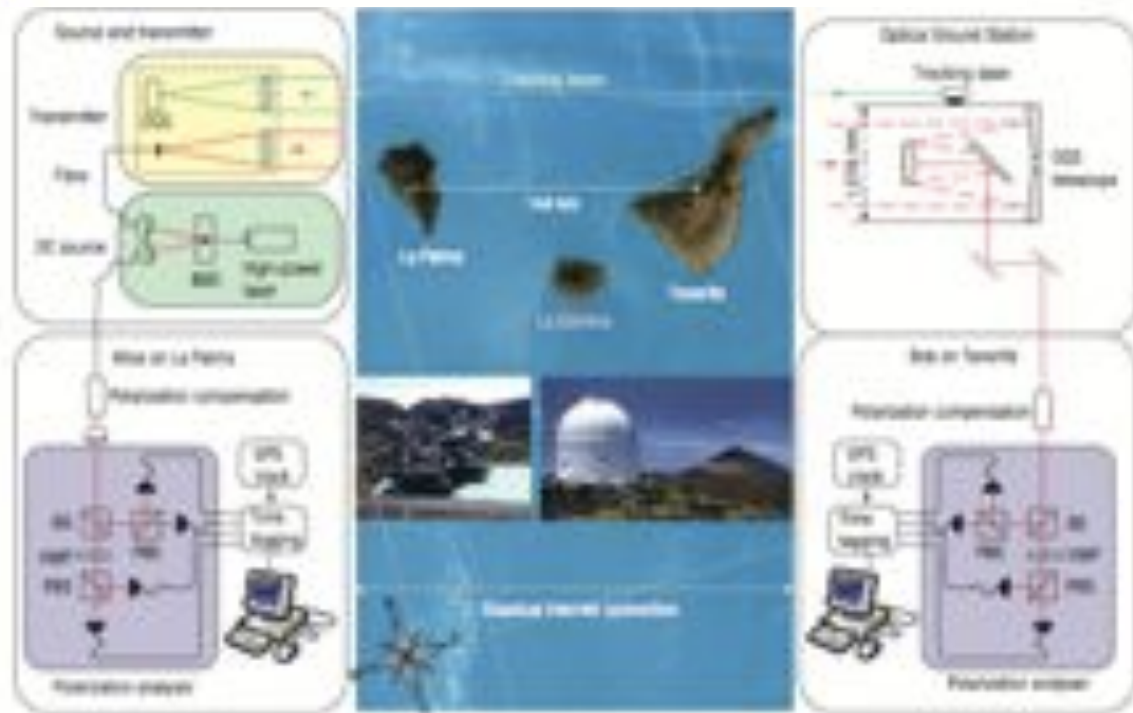


# Bell Inequality Violation

Entanglement-based quantum communication over 144 km

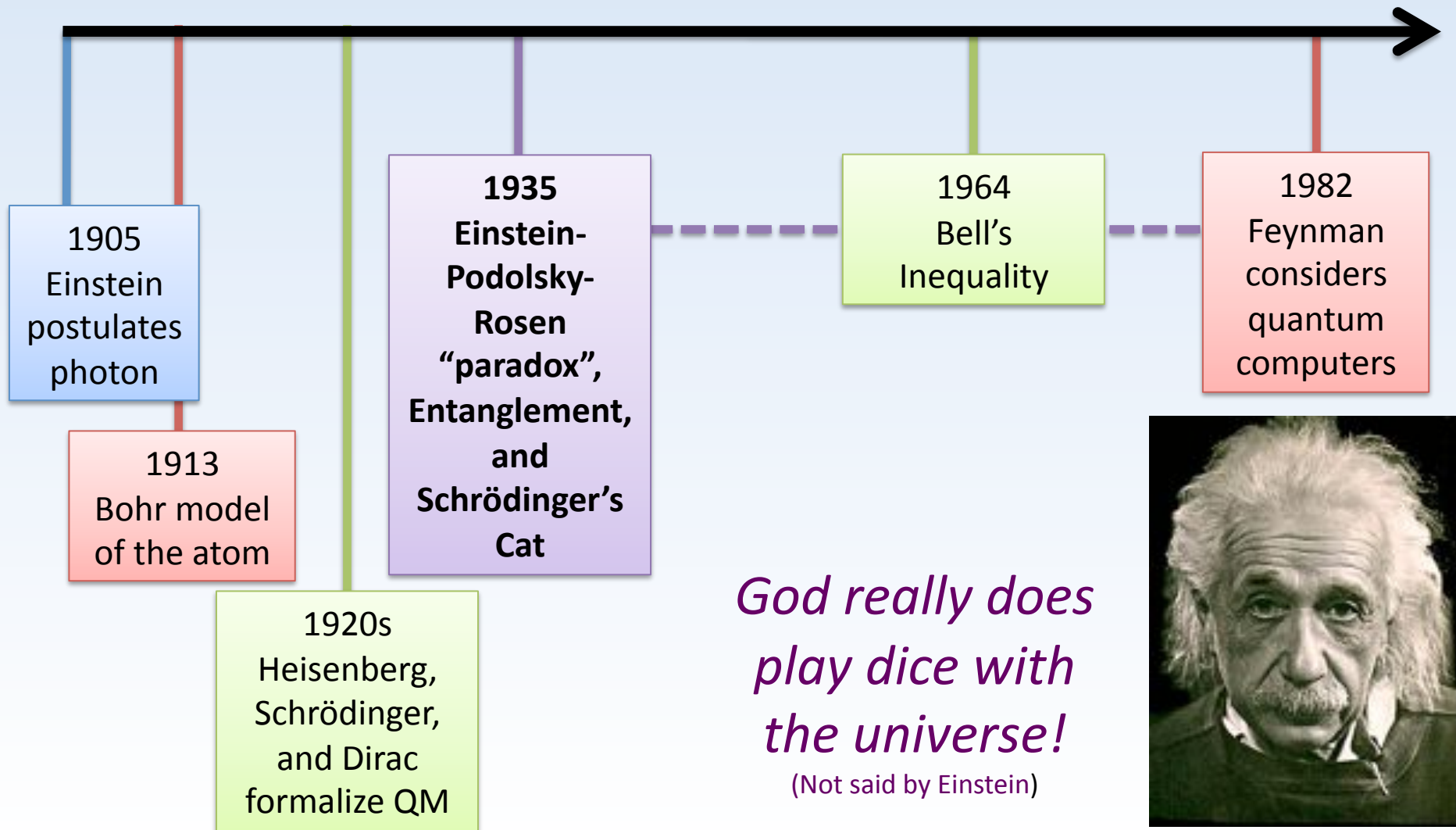
$$S = 2.508 \pm 0.037$$

R. URSIN<sup>1\*</sup>, F. TIEFENBACHER<sup>1,2</sup>, T. SCHMITT-MANDERBACH<sup>3,4</sup>, H. WEIER<sup>1</sup>, T. SCHEIDL<sup>1,2</sup>,  
M. LINDENTHAL<sup>2</sup>, B. BLAUENSTEINER<sup>1</sup>, T. JENNEWAIN<sup>2</sup>, J. PERDIGUES<sup>5</sup>, P. TROJEK<sup>3,4</sup>, B. ÖMER<sup>6</sup>,  
M. FÜRST<sup>4</sup>, M. MEYENBURG<sup>6</sup>, J. RARITY<sup>7</sup>, Z. SODNIK<sup>8</sup>, C. BARBIERI<sup>9</sup>, H. WEINFURTER<sup>3,4</sup>  
AND A. ZEILINGER<sup>1,2\*</sup>



Nature Physics **3**, 481 (2007)

# Timeline of QM + Entanglement



# Feynman's Epigram I



- ***Nobody*** understands quantum mechanics!

---Richard Feynman, 1964

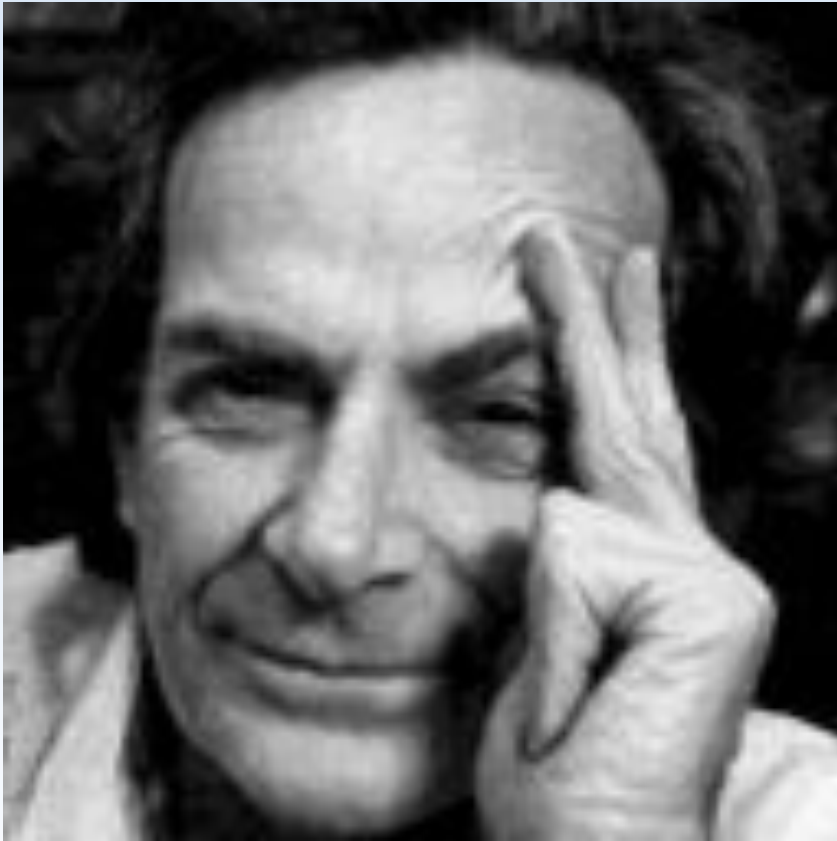
# Feynman's Epigram II



- We have always had a great deal of difficulty understanding the world view that quantum mechanics represents.
- At least I do, because I'm an old enough man that I haven't got to the point that this stuff is obvious to me.

---Richard Feynman, 1982

# Feynman's Epigram II



- Okay, I still get nervous with it ...
- You know how it always is, every new idea, it takes a generation or two until it becomes obvious that there's no real problem.
- ***I cannot define the real problem, therefore I suspect there's no real problem, but I'm not sure there's no real problem.***

---Richard Feynman, 1982

# Tomorrow

- Quest for quantum computer
- Superconducting Circuits = Giant Artificial Atoms interacting with microwave photons
- My work hunting for bigger and better Schrödinger cats

