Experience, Measurement, and The Collapse of Quantum Mechanics

A Modern View

By Eric L. Michelsen

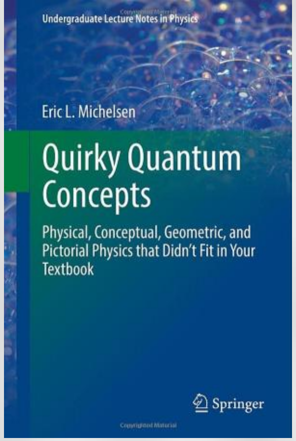
Presentation to the
Fleet Science Center, 7/1/2019.

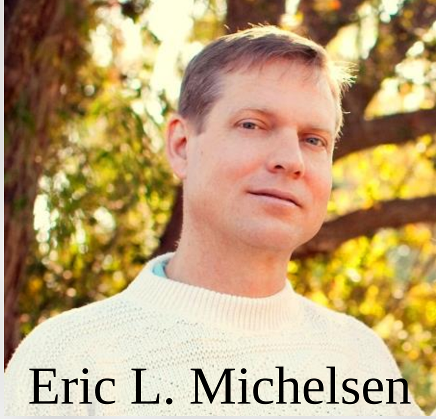
Probably, most of what you've heard about Quantum Mechanics is wrong

- E.g., reality is *not* subjective
  - We *don't* get to choose our own reality
- But some of what you've heard is true:
  - Particles *can* have components in two (or more) places at once
    - Each component evolves in time as if it were the whole particle (the whole mass, whole charge, whole spin)
  - We'll come back to this soon
- Even most physicists get QM wrong
  - Though more and more physicists *are* coming out to "set the record straight"
  - We need to update our physics education
    - Including general public education
- Beware of the Internet
  - Especially on technical subjects like physics
  - The most reliable sites are professors'

Who am I?

- Background
  - PhD Physics UCSD, June 2010
    - Research: Lunar Laser Ranging
    - Study of gravity, aka General Relativity
  - My book on quantum mechanics was published in February, 2014, by Springer
    - Quirky Quantum Concepts
    - It's on Amazon!
    - Technical book for serious scientists & engineers
  - BSEE: electrical engineer for a few decades
    - Software Engineering
    - Integrated Circuits: circuit & device design
    - Digital Signal Processing, data communication
- Interests:
    - Human Rights
    - Quantum Field Theory
    - Medical physics
    - Scuba diving (again someday)
  - Upcoming: Fleet-sponsored panel discussion at Comic-Con
    - "Quantum time travel" as depicted in *Endgame*




Eric L. Michelsen

Mythbusters Ep. 104



Big Bang Theory, S3E23

Outline

- The Foundations of Science
- Three steps to Quantum Mechanics
  - Probabilistic reality
  - Superpositions and Interference
  - Entanglement
- The “measurement problem”
- Motivation for decoherence
- Decoherence overview
- Complementarity?
  - The four distractions
- Consistency, and role of the observer
- Bonus: speculation on free will

Thanks to Dr. Eve Armstrong for very helpful comments and suggestions

The purpose of physics is to relate mathematics to reality

Single Stage Fehskens-Malewicki Equations:

burnout velocity:

$$v_b = \sqrt{\frac{F - mg}{k}}\, \tanh\left[\frac{t_b}{m}\sqrt{k(F - mg)}\right]$$

burnout altitude:

$$y_b = \frac{m}{k}\ln\left\{\cosh\left[\frac{t_b}{m}\sqrt{k(F - mg)}\right]\right\}$$

coast altitude:

$$y_c = \frac{m_b}{2k}\ln\left[\frac{k v_b^2}{m_b g} + 1\right]$$

coast time:

$$t_c = \sqrt{\frac{m_b}{g k}}\, \tan^{-1}\left[v_b\sqrt{\frac{k}{g m_b}}\right]$$

Where:

$k = \frac{1}{2}\rho C_D A$

ρ = atmospheric density

C_D = drag coefficient

A = frontal area

t_b = burn time

F = average thrust

m = average thrusting mass

m_b = burnout mass

g = acceleration due to gravity

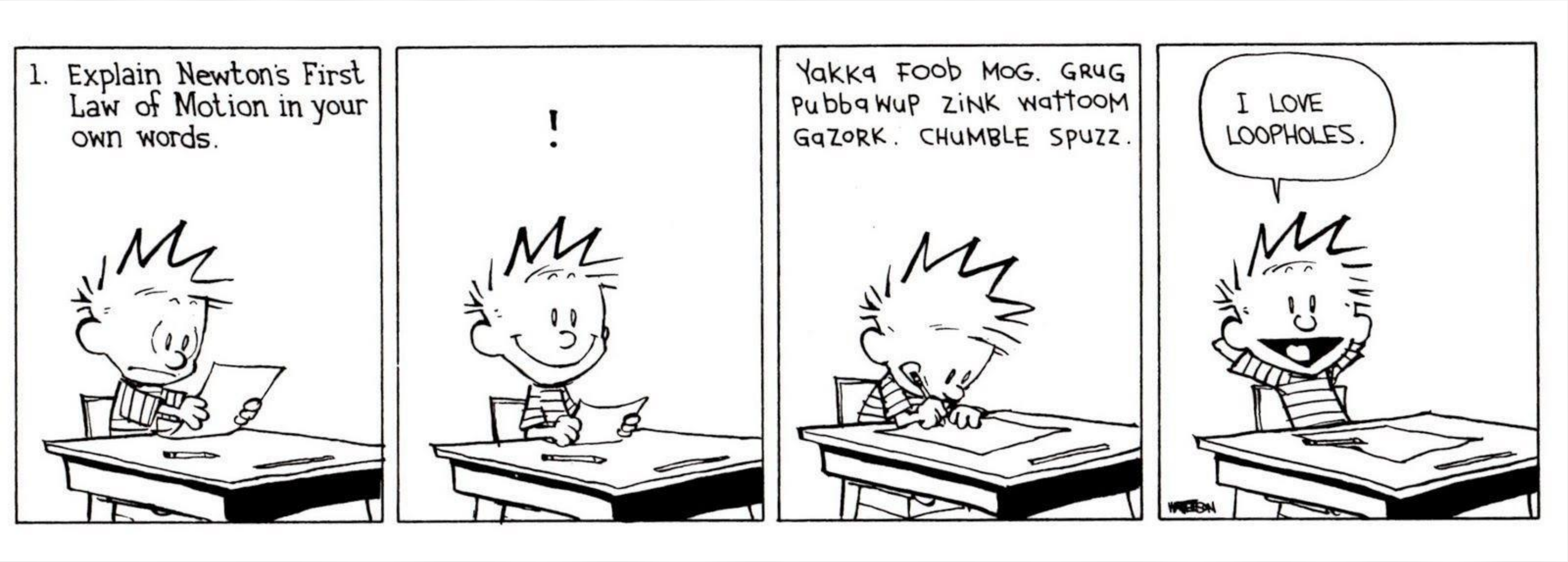
Return

$$-c^2 \frac{dv}{\left(c^2 - v^2\right)\left(\left(1-\gamma_e x\right)v + \gamma_e x e\right)} = \frac{dm}{m}$$

$$where \quad dm < 0$$

Physics is not math

- Physics includes math …
  - But we don't hide behind it
  - Without a conceptual understanding, math is gibberish
- No math needed to appreciate this talk
  - But I'll show you what it looks like

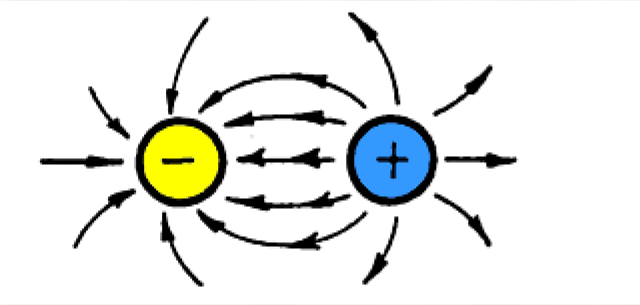


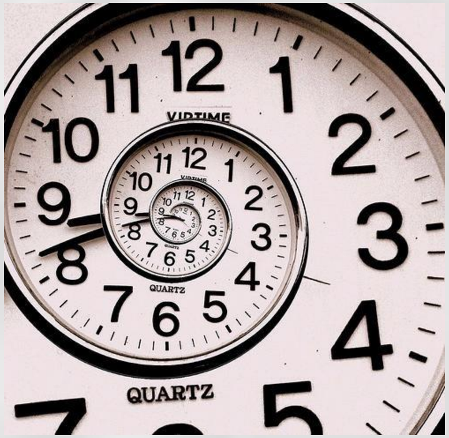
Fundamental (macroscopic) measurable quantities

- How many fundamental (macroscopic) *measurable* quantities are there?
  - What are they?

Four fundamental (macroscopic) quantities

- MKSA
  - distance: meter, m
  - mass: kilogram, kg
  - time: second, s
  - charge: coulomb, C
- Science relates these measurements in formulas/equations: $F = ma$

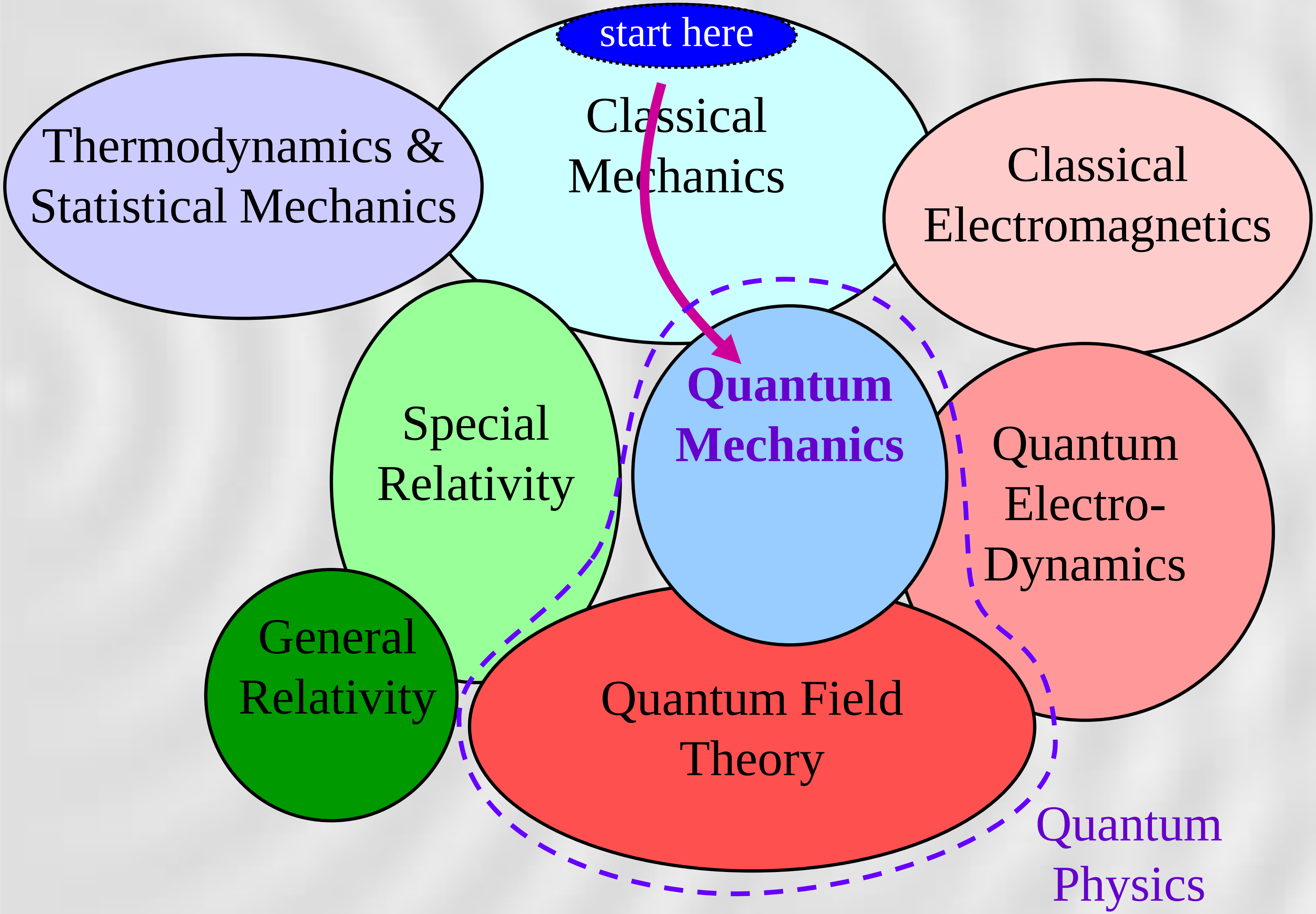




Science goals

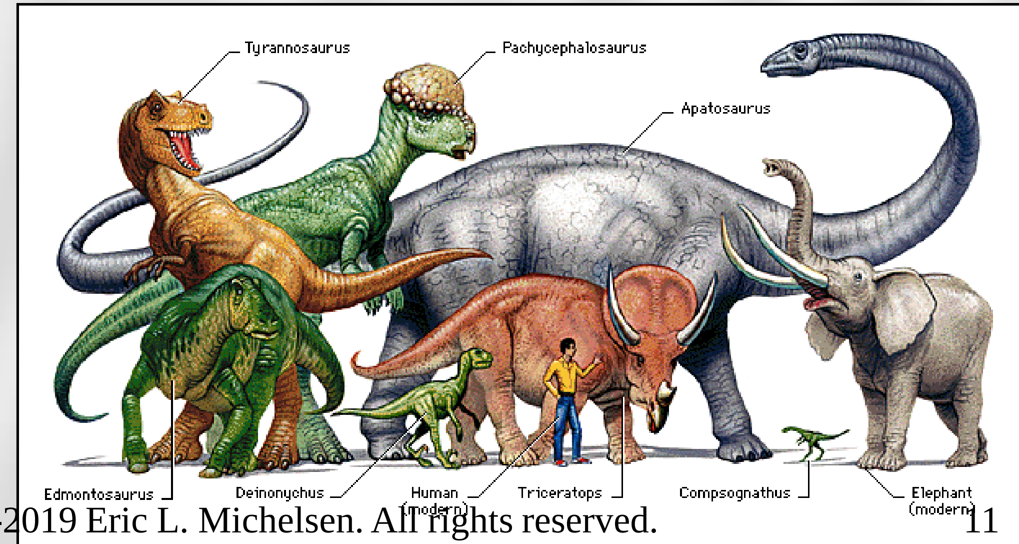
- “Now in the further development of science, we want more than just a formula.
    - First we have an observation ...
    - Then we have numbers that we measure ...
    - Then we have a law which summarizes all the numbers.
- But the real *glory* of science is that *we can find a way of thinking* such that the law is *evident*.” - Richard Feynman, *Feynman Lectures on Physics*, Volume 1, p26-3.

The pedagogical structure of physics

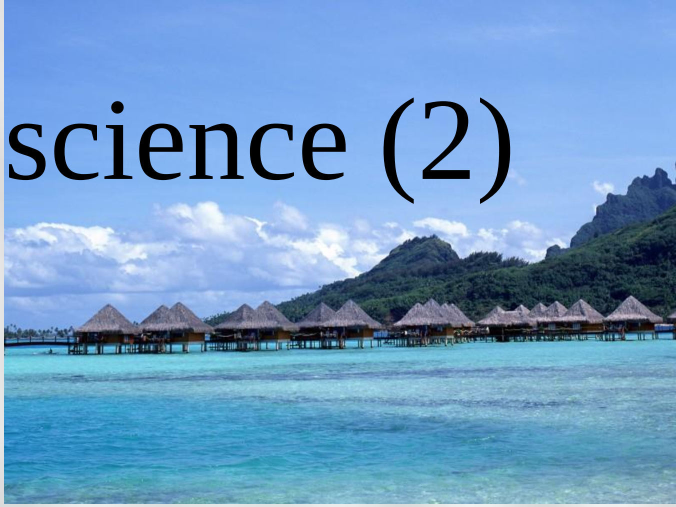


The three keywords of science (1)

- **Speculation**: a guess
  - Possibly hinted at by evidence, but not well supported
    - The sky is blue because light reflected from the blue ocean illuminates it (not true)
    - Some dinosaurs had green skin (unknown)
  - Every scientific fact and theory started as a speculation



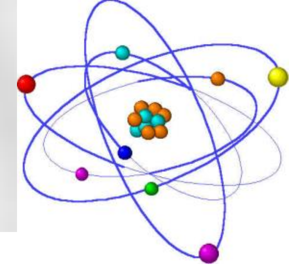
The three keywords of science (2)

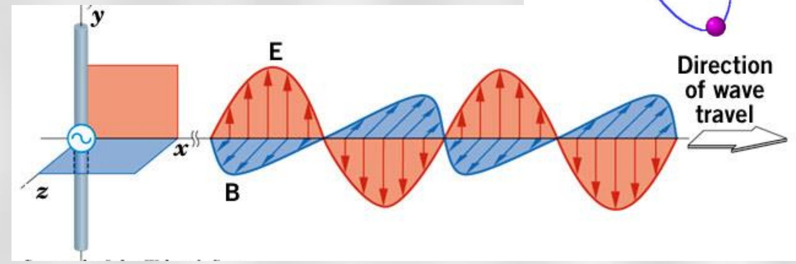


- **Fact**: A small piece of information
  - Backed by solid evidence
  - In hard science, usually repeatable evidence
    - The sky is blue
    - Copper is a good conductor of electricity

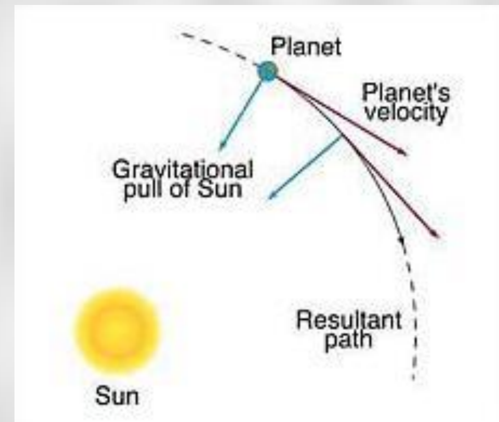
- A fact is beyond genuine doubt
  - Despite arguments that "nothing can be proved 100%"
- If someone disputes a fact, it is still a fact
  - I say the earth is flat
  - Does that mean there is a "debate" about the earth's shape?
- "If a thousand people say a foolish thing, it is still a foolish thing."

The three keywords of science (3)

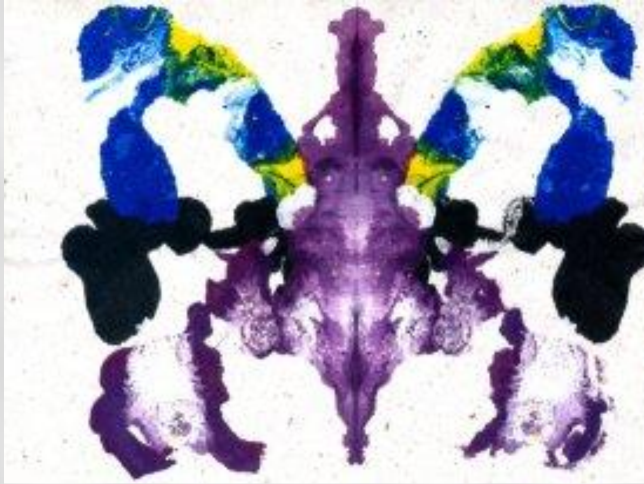




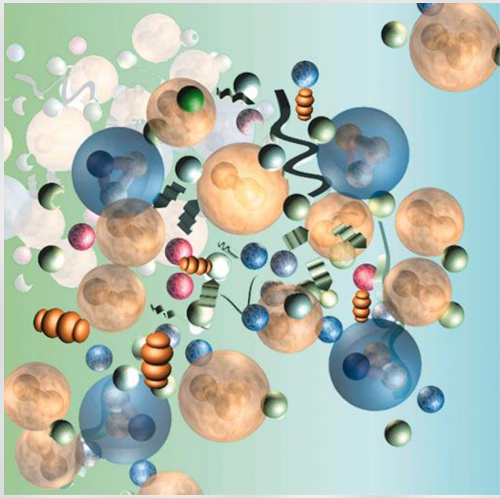
- **Theory**: The highest level of scientific achievement
  - A *quantitative, predictive, testable* model that unifies and relates a body of facts
  - Every scientific theory was, at one time, *not* generally accepted
  - A theory becomes accepted science *only* after being supported by overwhelming evidence
    - A theory is *not* just a speculation
    - Atomic theory of matter
    - Maxwell's electromagnetic theory
    - Newton's theory of gravity
    - Germ theory of disease



“Meaning” is not science



- Asking “What is the meaning of the science?” is *not* a scientific question
  - Perhaps it is a philosophical question
- “Meaning” is rooted, essentially by definition, in our everyday experience
  - But there is no reason to expect that the world *beyond* our experience should be explainable *by* our experience

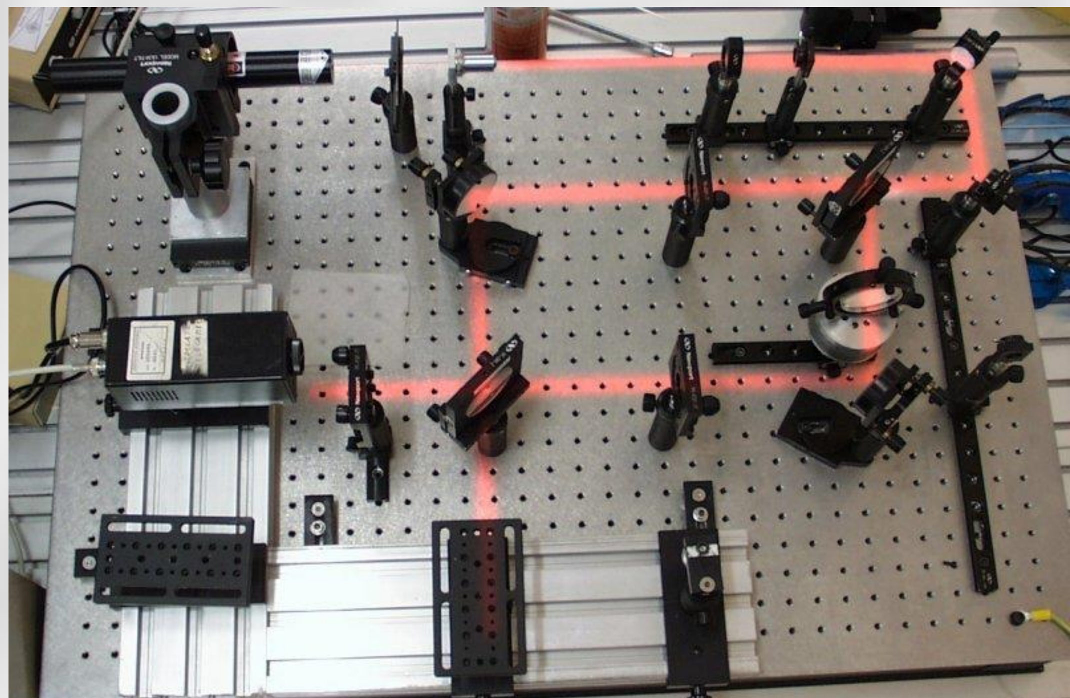


- As a scientist, I don’t have a “meaning” for quantum physics
  - It is what it is:
    - The most accurate physical theory ever developed
    - It doesn’t matter how I feel about it

What is the nature of quantum mechanics?

- Is it mystic?
- Or is it science?

It's this one

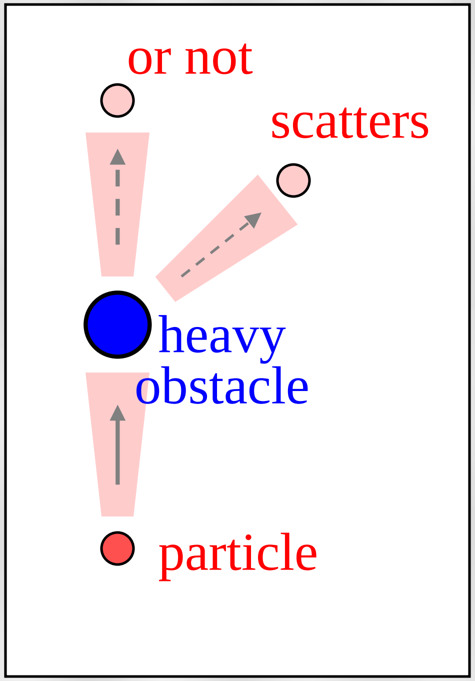


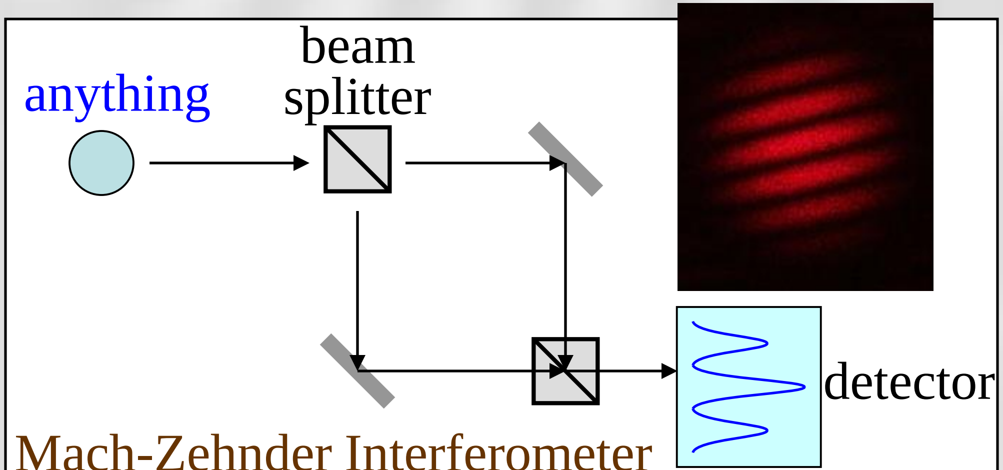
Three steps to quantum mechanics

1. Reality is probabilistic
2. Superpositions and interference
3. Entanglement

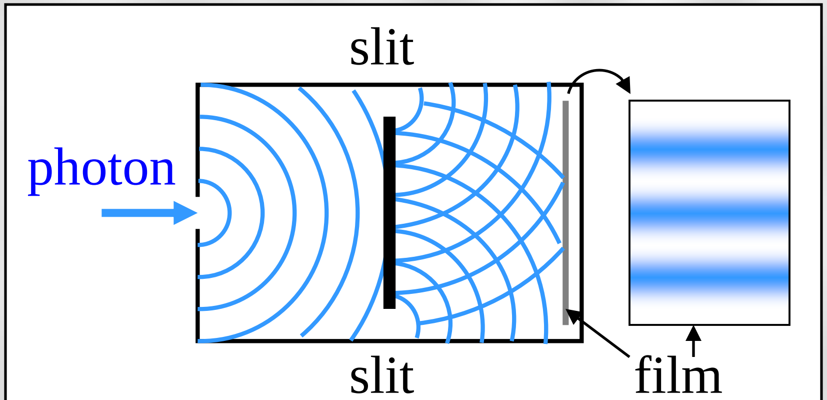
(1) Reality is probabilistic

- The *exact* same setup, measured multiple times, produces different results
  - Sometimes a particle scatters, sometimes it doesn't
- If two possible outcomes never cross paths, they are indistinguishable from a coin toss
  - Classical probability (nothing weird)
- If two possible outcomes are recombined, we get **interference**
  - Even from one particle at a time
  - Everything is a wave (even particles are waves)





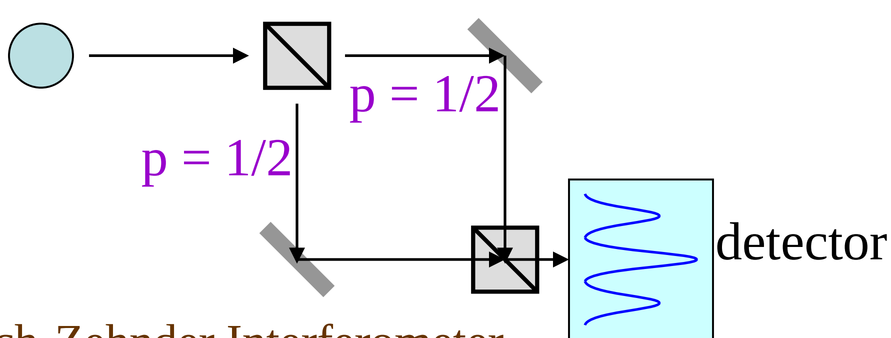
Mach-Zehnder Interferometer



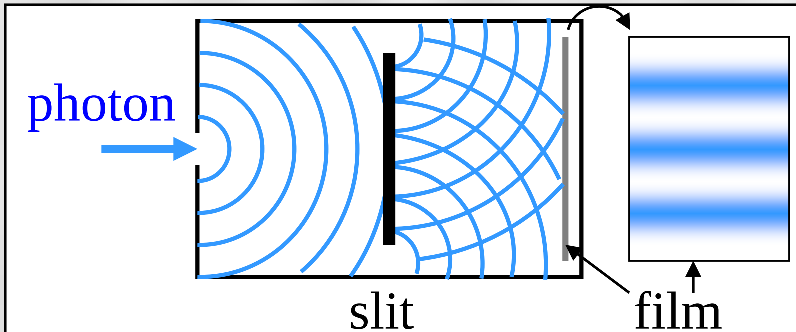
Double-slit (Young's experiment)

(2) Interference implies "superpositions," not classical probabilities

- The particle "divides" and pieces takes both paths
  - Each component gets a "weight," or fraction
    - Say, ½ and ½, but it could be 1/10 and 9/10, etc.
  - But ... each component behaves as if it were the whole particle (whole mass, whole charge, whole spin, ...)
  - And in the end, for each particle, only *one* component is observed
- Quantum interference requires two things:
  - Recombining two components of a single quantum state
  - Many "trials"
    - Possibly of one particle each



Mach-Zehnder Interferometer



Double-slit (Young's experiment)

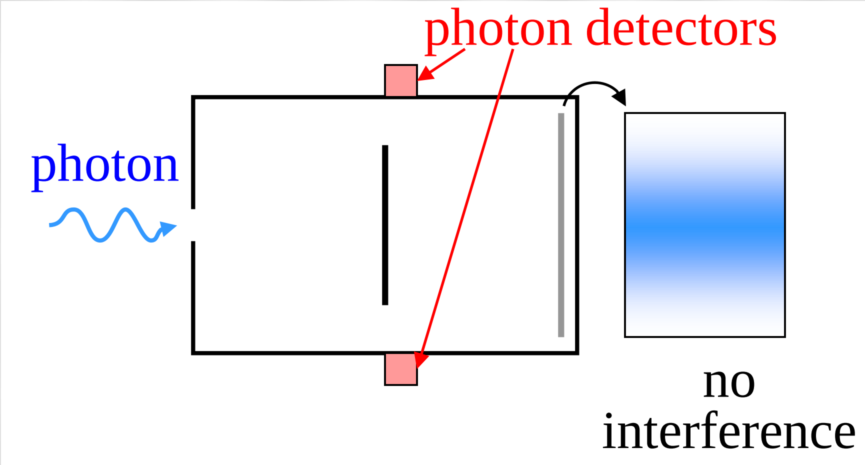
Such interference is the hallmark of quantum mechanics

- If a particle interferes, it's quantum
  - If it doesn't, it's classical

- But why are some things classical, and some quantum?

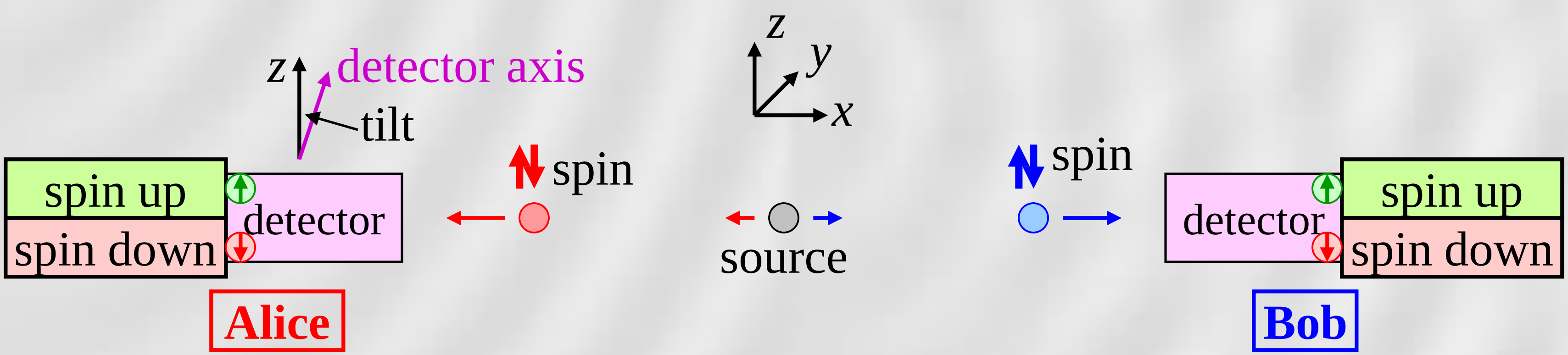
Which way did it go?

- If we try to see "which way" the photon went, we prevent interference
  - One photon triggers only one detector
    - And no interference
  - Suggests "complementarity:" a photon is either a wave, or a particle, but not both at the same time
    - But how does it know which to be?

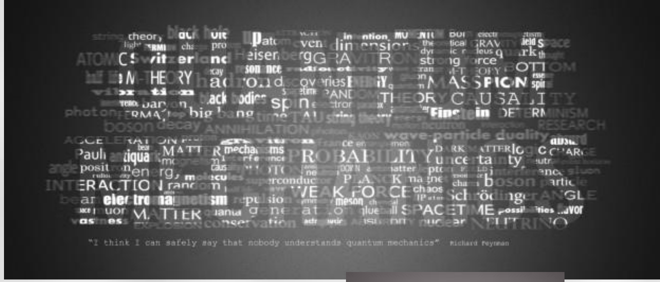


(3) Is Entanglement Real?

- A spin zero source emits 2 particles at a time:
  - Randomly, one is up (positive),
    the other is down (negative)
- Alice & Bob each measure spin
  - The sum is zero (every time)
- Now, we tilt Alice's measuring device, introducing some errors
  - Therefore, sometimes their measurements are the same (both up or both down)
- Now, we tilt her device 90° off: she is wrong ½ the time
  - And we also tilt Bob's device, but the other way: he is also wrong ½ the time
  - Classically: ¼ of the time, they're both right;
    ¼ of the time, they're both wrong
    - The net effect: the measurements add to 0 half the time

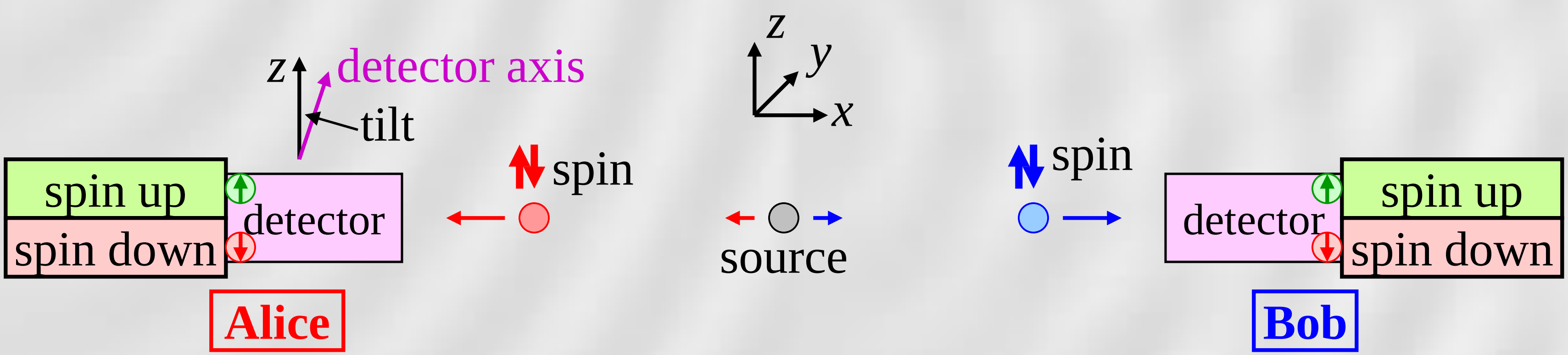


The winner, and still champeen is ...



- Recap:
  - A spin zero source emits 2 particles at a time:
    - Randomly, one points up (positive), the other points down (negative)
  - Alice's measuring device gets tilted; she is wrong ½ the time
  - Bob's device gets tilted the other way: he is also wrong ½ the time
  - Classically, the net effect: the measurements add to 0 half the time
- In the actual experiment: the spins *always* measure the same, they *never* add to zero
  - As predicted by quantum mechanics, because the particles are *entangled*
    - No matter how far apart are Alice and Bob
  - Quantum mechanics is right; classical mechanics is wrong
- Entanglement *is* "spooky action at a distance"
  - Reality is either nonlocal, or noncausal
    - In light of relativity, those are actually the same thing

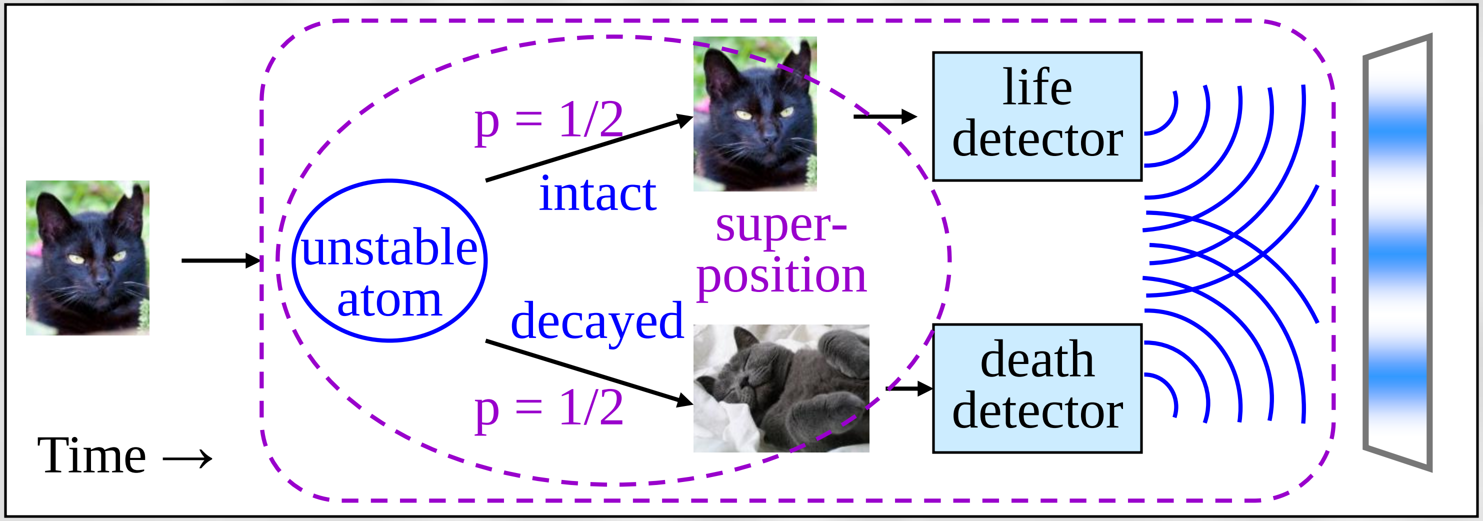
It's real!



Can we entangle a cat?

Erwin Schrödinger

- Consider a cat in a box, with an unstable atom rigg poison
  - If the atom remains intact, the cat is alive
  - If the atom decays, the cat is dead
  - After one half-life the *atom* is in a *superposition* of ½ decayed and ½ intact
    - It is *not* a classical probability of decay: *not* "decayed" *or* "intact", because ...
    - In principle, the two *atom* states can be recombined and *interfere*
    - But this implies the *cat* is in a **superposition** of dead and alive
    - However, experiments never show such large-scale interference!



The cat is **entangled** with the atom, and then the detectors, until we observe the result.

The "measurement problem"

- Why don't we ever measure a superposition?
  - What would that even mean?
  - We always measure a definite value
- Why does an intermediate measurement prevent interference?
- For decades, it's been said, "Measurement 'collapses' the wave-function (quantum state)."
  - Meaning that a measurement eliminates a superposition in favor of a more-definite state
    - A measurement picks *one* component, and makes it "real"
  - But what, exactly, is a "measurement"?
    - Can a chimpanzee make a measurement?
    - A cat? An insect? A robot?





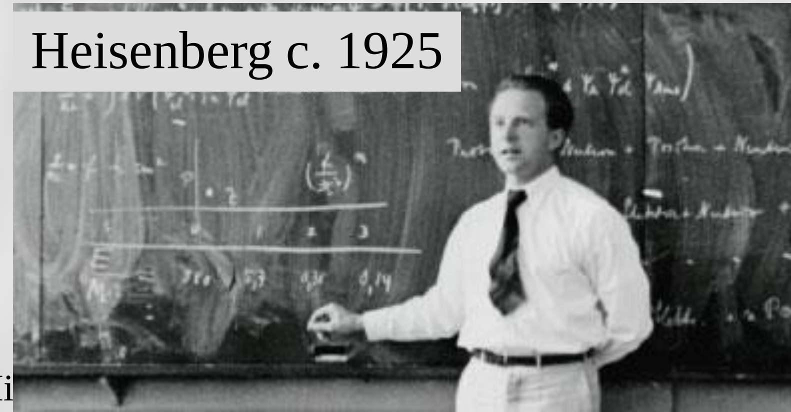
"Decoherence" theory solves the measurement problem

- Now that we know entanglement is real, we must resolve the measurement problem
  - There are no measured superpositions, so ...
  - Where is the transition from quantum to classical (i.e., from particle to wave)?
- What is a measurement?
  - I.e., when does the quantum state collapse?
    - Who can collapse it?

- This has been resolved for 30 years
  - As of 1980s
  - But even most physicists don't understand it

It's time to bring QM into the modern era

- For both scientists and the general public
- QM is ~90 years old
    - But it is still taught like the 1930s
- A surprising amount of current *scientific* literature is devoted to "the meaning" of QM
    - A disturbing amount of decoherence literature is defending basic scientific principles, such as predictions and testability
- Decoherence has been around since the 1980s
    - It has been surprisingly neglected



Heisenberg c. 1925

Decoherence overview

quantum state

external forces

$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\psi + V\psi$$

changes in time

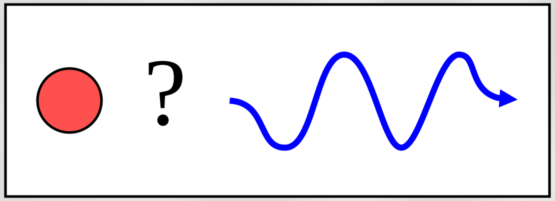
- The decoherence model explains everything from two principles:
  - Time evolution, according to the Schrödinger Equation
    - Relates state changes over time to the current state and external forces
  - "Mini-collapse" when a result is observed (by me!)

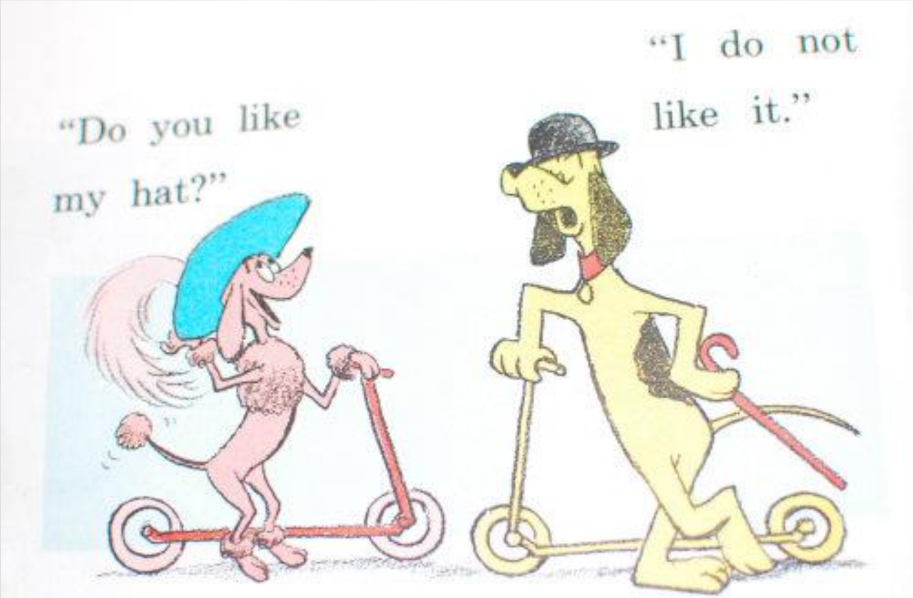
my words

- IMHO
  - Decoherence is the simplest, most intuitive Quantum Mechanics model
    - It is correct: It predicts the outcomes of experiments
    - Most consistent with other laws of physics

Ye olde complementarity (c. 1929)

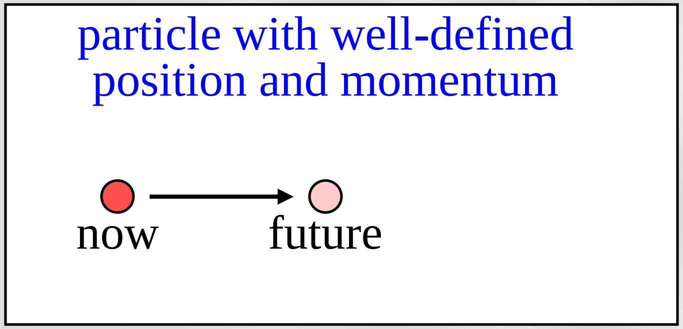
- Prevention of interference led to speculation of a "Wave-particle duality," aka "complementarity"
  - Particles behave like either a wave or a particle, but not both
  - Which one depends on the experiment
- There are 4 completely different phenomena that have all been called examples of "complementarity"
  - Bohr microscope
  - "Fake" decoherence
  - Measurement entanglement
  - "Real" decoherence

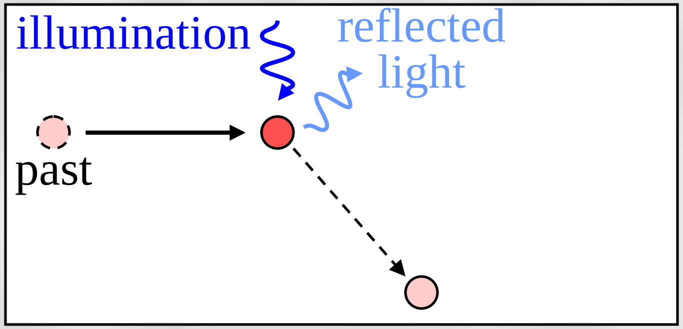




(1) Bohr microscope

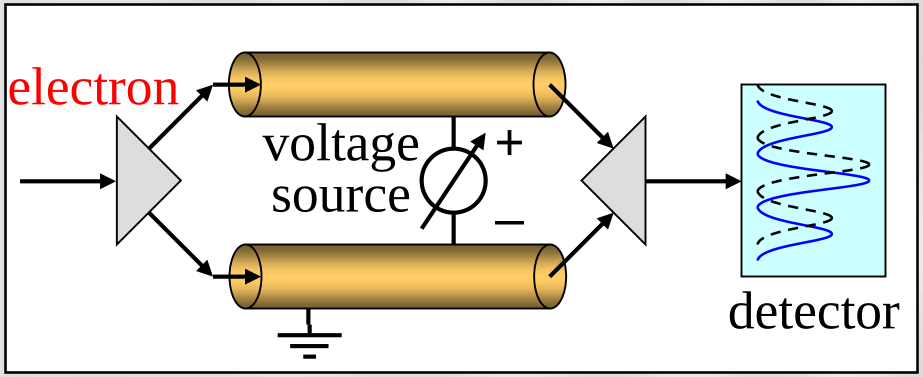
- Position-momentum uncertainty is from measurement clumsiness
  - Measurement "bumps" the particle out of its current state
  - Prevents an interference pattern
- I never liked this
  - Belies the nature of wave-functions
    - It's not: a particle has a well-defined momentum and position, but nature is mean, and won't let you know them both
    - It is: A particle cannot *have* a well-defined position *and* momentum
  - The error motivates a search for a "kinder, gentler" measuring device
    - Such a device exists, and disproves "clumsy measurement"! (More soon.)

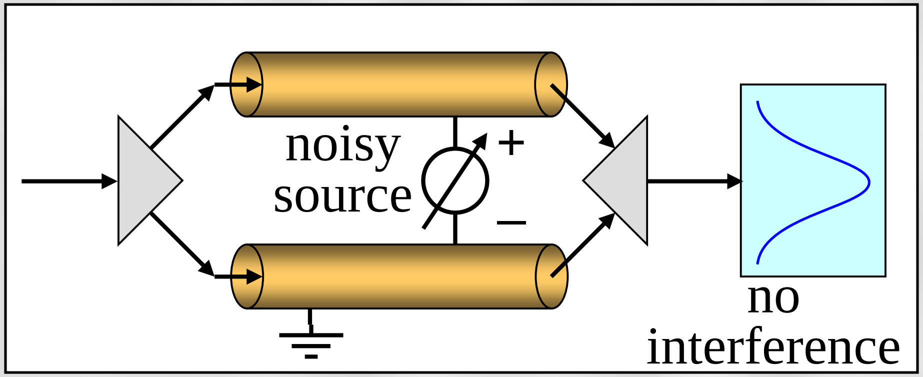




(2) “Fake” Decoherence (skip)

- Consider a 2-slit experiment where the energy of one path is controllable
  - Position of interference pattern is then controllable
- What if energy is uncontrollable and unrepeatable, i.e. **noise**?
  - Interference pattern moves randomly, washes out
- Uncontrolled and unrepeatable energy transfer leads to classical probabilities
  - Loss of coherence ~10^{-12} s





(3) Measurement device entanglement

- Excited atom radiates a photon into the cavities

$$\left|a_{up}\right\rangle + \left|a_{dn}\right\rangle \Rightarrow \left|a_{up}\right\rangle\left|\gamma_{up}\right\rangle + \left|a_{dn}\right\rangle\left|\gamma_{dn}\right\rangle$$

entanglement!

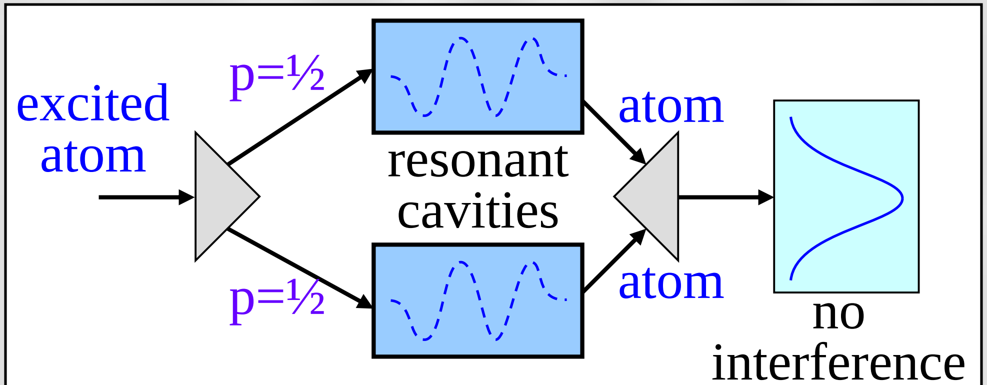
  - Is it a measurement?
  - Does it cause collapse?

$$\Pr(x) = \left|\psi_{up}(x)\left|\gamma_{up}\right\rangle + \psi_{dn}(x)\left|\gamma_{dn}\right\rangle\right|^2$$

interference terms

$$= \psi^*_{up}\psi_{up} + \boxed{\cancel{\psi^*_{up}\psi_{dn}\left\langle\gamma_{up}\middle|\gamma_{dn}\right\rangle} + \cancel{\psi^*_{dn}\psi_{up}\left\langle\gamma_{dn}\middle|\gamma_{up}\right\rangle}} + \psi^*_{dn}\psi_{dn}$$

$\rightarrow$ no interference because $\left\langle\gamma_{up}\middle|\gamma_{dn}\right\rangle = \left\langle\gamma_{dn}\middle|\gamma_{up}\right\rangle = 0$



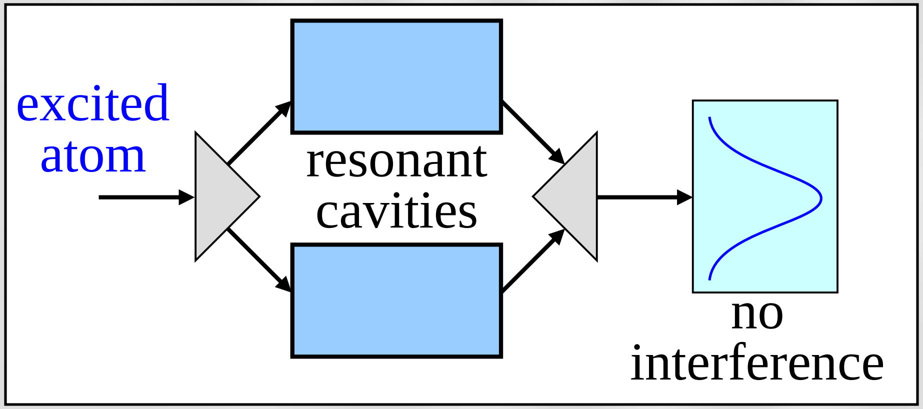
Scully, et. al., Nature, 351, 9-May-91, p111.

1. The presence or absence of an observer is irrelevant.

2. The non-overlap of the *measurement (photon)* states is important.

Measurement device entanglement (cont.)

- This *is* a kinder, gentler measurement
  - The radiated photon has insignificant effect on the atom's center-of-mass wave-function
  - Disproves the Bohr microscope "clumsy measurement" idea



QNDM: quantum non-demolition measurement: we measure "which way" the atom went, but without disturbing it!

Partial coherence: What if the entangled states overlap?

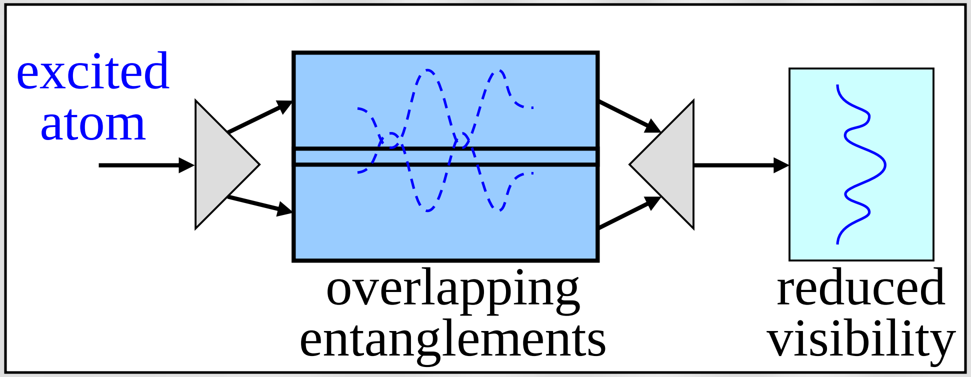
- Then interference is possible
  - With *reduced visibility* (smaller wiggles)

$$\Pr(x) = |sys(x)|^2 = \left|\psi_{up}(x)|\gamma_1\rangle + \psi_{dn}(x)|\gamma_2\rangle\right|^2$$

$$= \psi^*_{up}\psi_{up} + \boxed{\psi^*_{up}\psi_{dn}\langle\gamma_1|\gamma_2\rangle + \psi^*_{dn}\psi_{up}\langle\gamma_2|\gamma_1\rangle} + \psi^*_{dn}\psi_{dn}$$

$\rightarrow$ interference because $\langle\gamma_1|\gamma_2\rangle = \langle\gamma_2|\gamma_1\rangle \neq 0$

The overlap of the entangled states sets the *visibility* of any interference

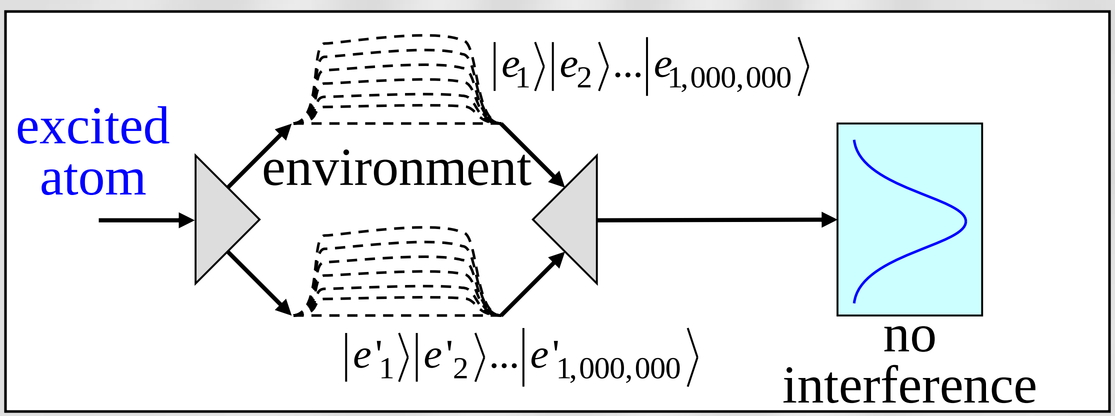


(4) "Real" decoherence

- The two components of the split particle interact with their macroscopic environment
  - Evolving through a cascade of progressively more entanglement with time
    - Every air molecule it encounters introduces another entanglement
  - Even though the environmental states may have large overlap
    - The product of millions of numbers < 1 ≈ 0

$$\psi = \psi_{up} + \psi_{dn} \rightarrow \psi_{up} \left| e_1 \right\rangle \left| e_2 \right\rangle \ldots \left| e_{1,000,000} \right\rangle + \psi_{dn} \left| e'_1 \right\rangle \left| e'_2 \right\rangle \ldots \left| e'_{1,000,000} \right\rangle$$

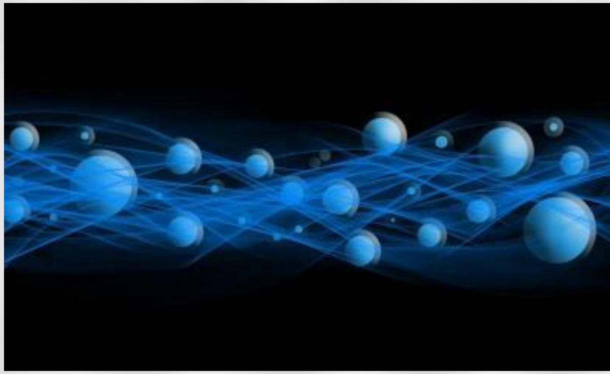
$$\text{interference terms} \propto \left\langle e_1 \middle| e'_1 \right\rangle \left\langle e_2 \middle| e'_2 \right\rangle \ldots \left\langle e_{1,000,000} \middle| e'_{1,000,000} \right\rangle \approx 0$$



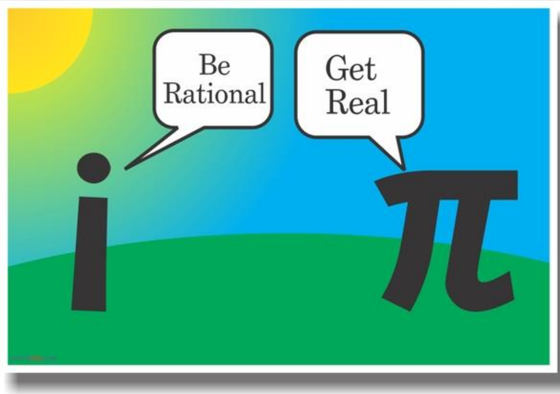
"Decoherence" *is* entanglement.

"Real" decoherence is why we don't measure superpositions

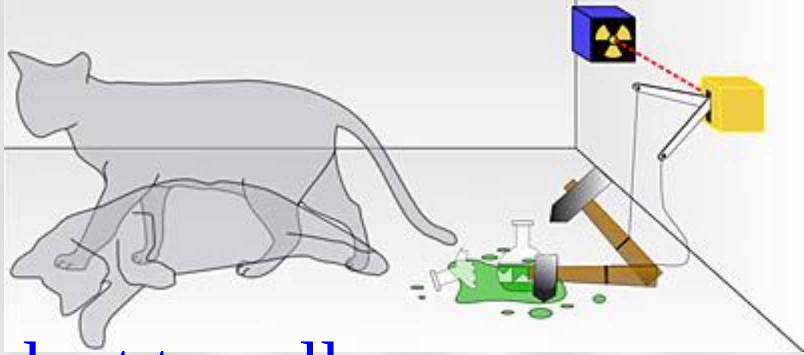
- Real experiments are inevitably connected to their surrounding environment
- Macroscopic experiments become entangled with billions of particles ("subsystems") in the environment



  - This means particles decohere extremely quickly: ~10^{-18} s
- The decoherence model still requires a [mini]collapse:
  - Consistency: after I see a measurement, all other components of the superposition disappear (the wave function collapses)
    - In the decoherence model, this is the "weirdest" phenomenon of quantum mechanics
  - The rest is just a deterministic time evolution of the quantum state according to the Schrödinger equation
    - Including superpositions and entanglement



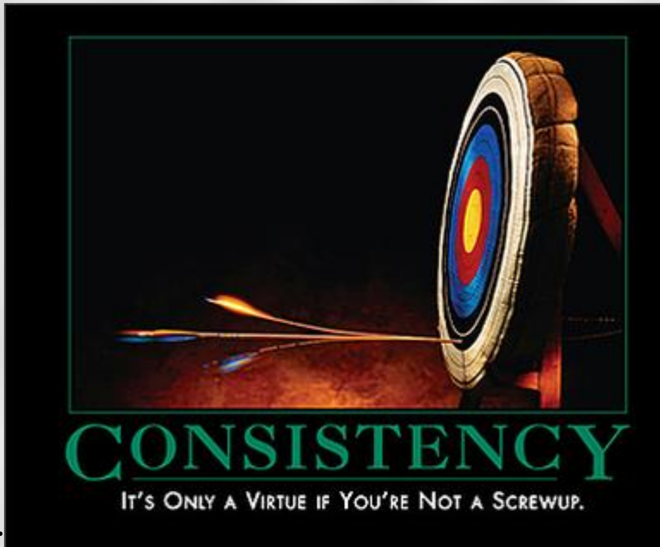
Decoherence vs. collapse: what's the difference?



- Total loss of coherence is equivalent to collapse
  - It doesn't matter what causes loss of coherence
- Both total loss of coherence *and* (old-fashioned, mythical) "collapse" lead to *classical* probabilities
  - Equivalent to: the particle is in *one* definite state, but we just don't know which state it is
- But the old collapse model has problems:
  - Cannot explain partial coherence (i.e., reduced visibility)
    - Collapse is binary: it happens or it doesn't
  - Decoherence is continuous: the overlap of entangled components smoothly becomes less
    - Interference visibility (wiggles) smoothly drops to zero

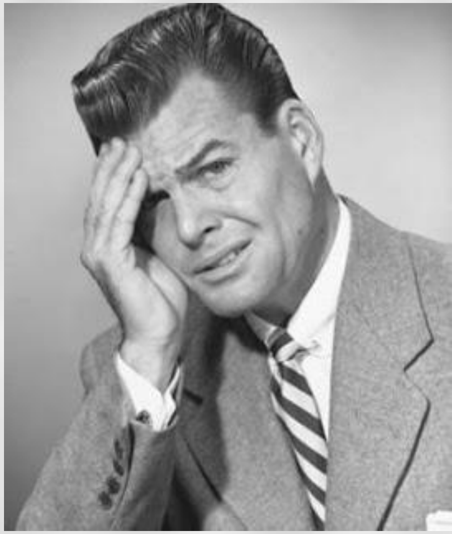
Mythbusting: Role of the observer (1)

- Observers are macroscopic (big)
  - When I look at a measurement device, my macroscopic body totally decoheres the possible measurement outcomes long before my brain can interpret the results
- Mini-collapse implies classical probabilities
  - This is more complete than old-fashioned collapse, because ...
    - It connects the measurement all the way to the observer with just entanglement and the Schrödinger Equation, and ...
    - It is fully consistent with partial coherence

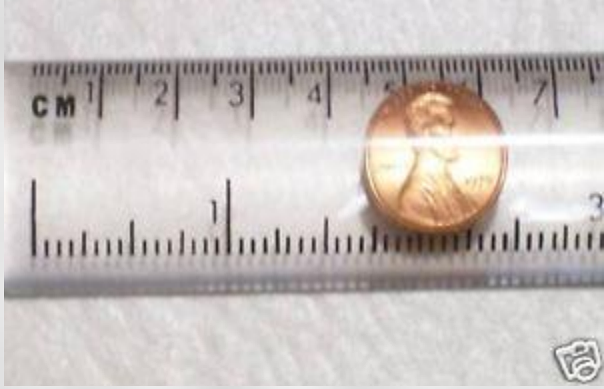


Role of the observer (2)

- Observers have no say in outcomes
  - No control
  - No choice
- Reality is *not* subjective
  - Science works, even Quantum Mechanics
  - Science predicts future events based on current information
- Quantum Mechanics is probabilistic, but complies with calculable probabilities
- Observation by one person (of a detector) has *no effect* on measurements by any other observers
  - So far as *I* am concerned, *you* are just a big quantum blob



Quantum summary



- A **measurement** is *defined* to be irreversible (for all practical purposes)
  - Implies total loss of coherence (no interference)
    - Classical probabilities
- The decoherence model is (IMHO) the simplest, most intuitive quantum model
  - Is just the Schrödinger Equation + mini-collapse
  - Eliminates any confusion about when is a measurement, when is collapse, etc.
- Reality is objective
- I don’t think “interpretations” of QM have any scientific basis
  - Angels on the head of a pin

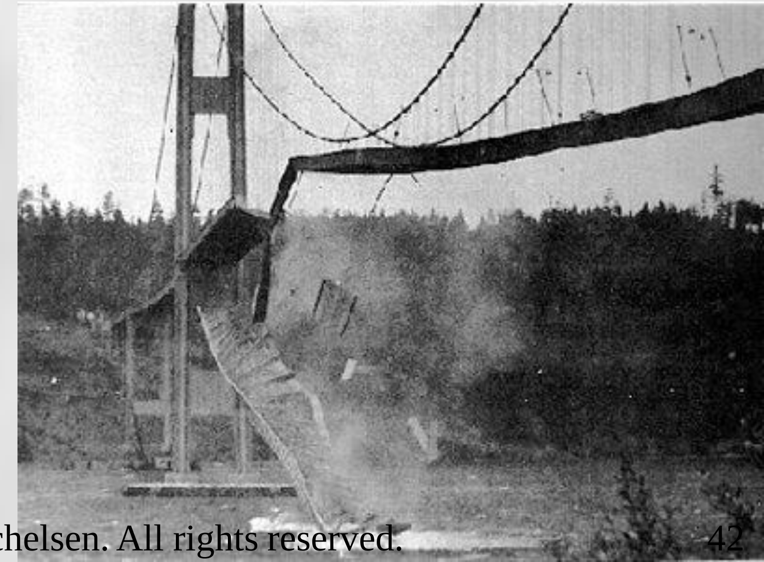
Philosophical indulgence: Is quantum probability an opening for free will?

- As a scientist, I don't talk much about such things
  - To date, there is no scientific input on this question
  - "Free will" is a hard thing to measure
- In my view, quantum uncertainty might be a venue for free will
  - Free will is consistent with entanglement
    - Free will is different than so-called "hidden variables"
  - In fact, free will is consistent with all the laws of QM
- As a humanitarian, I ask you to use your free will wisely


That's all Folks!

Consistency and collapse

- The "consistency postulate" requires a collapse somewhere along the line
  - Once I observe a result, all other possible outcomes disappear
    - Nonlinear (nonunitary?) collapse
  - Even in the decoherence model
- To allow for partial coherence, a theory (physical model) *must* defer any collapse to the last possible moment
  - All other time evolution simply follows the Schrodinger equation



$$\boxed{i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\psi + V\psi} \leftarrow \text{quantum state}$$

Aside: QM is more than just interference

- It's phase coherence between components of any superposition
  - E.g., Stern-Gerlach is *not* a measurement
- Unless we look at the result
  - Or any other macroscopic device gets entangled with the result