Entanglement, Decoherence, and The Collapse of Quantum Mechanics

A Modern View

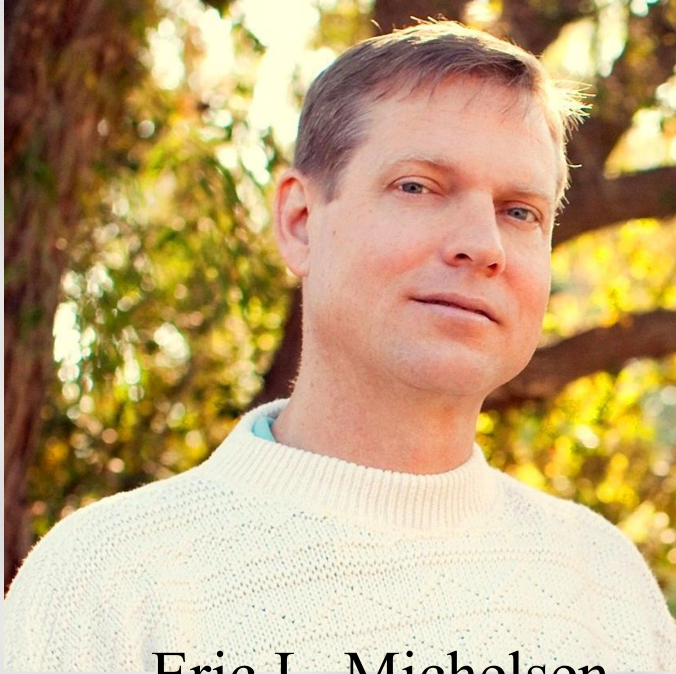
Presentation to the San Diego Philosophy Forum, May 27, 2014.

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

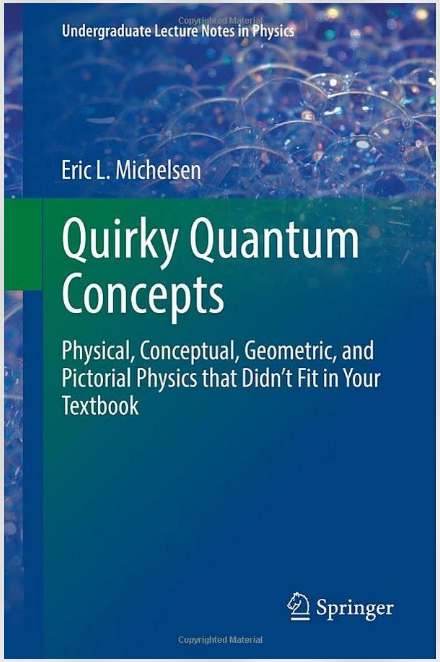
- Reality is *not* subjective
  - We *don't* get to choose our own reality
- But some of what you've heard is true:
  - Particles *can* have components in two (or more) places at once
    - Each component evolves in time as if it were the whole particle (the whole mass, whole charge, whole spin)
  - We'll come back to this soon
- Even most physicists get it wrong
  - We need to update our physics education
  - More and more physicists are coming out to "set the record straight" on QM
- 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!
    - It's a technical book for serious scientists
  - Software Engineering
  - BSEE: electrical engineer for a few decades
    - Integrated Circuits: circuit & device design
    - Digital Signal Processing
  - Interests:
    - Human Rights
    - Medical physics
    - Quantum Field Theory
    - Scuba diving (again someday)



Eric L. Michelsen



Outline

- Science Talk
- Prelude to Quantum Mechanics
  - Probabilistic reality
  - Superpositions
  - Interference
- The “measurement problem”
- Entanglement
- Motivation for decoherence
- Decoherence overview
- Complementarity?
  - The four distractions
- Consistency, and role of the observer
- 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

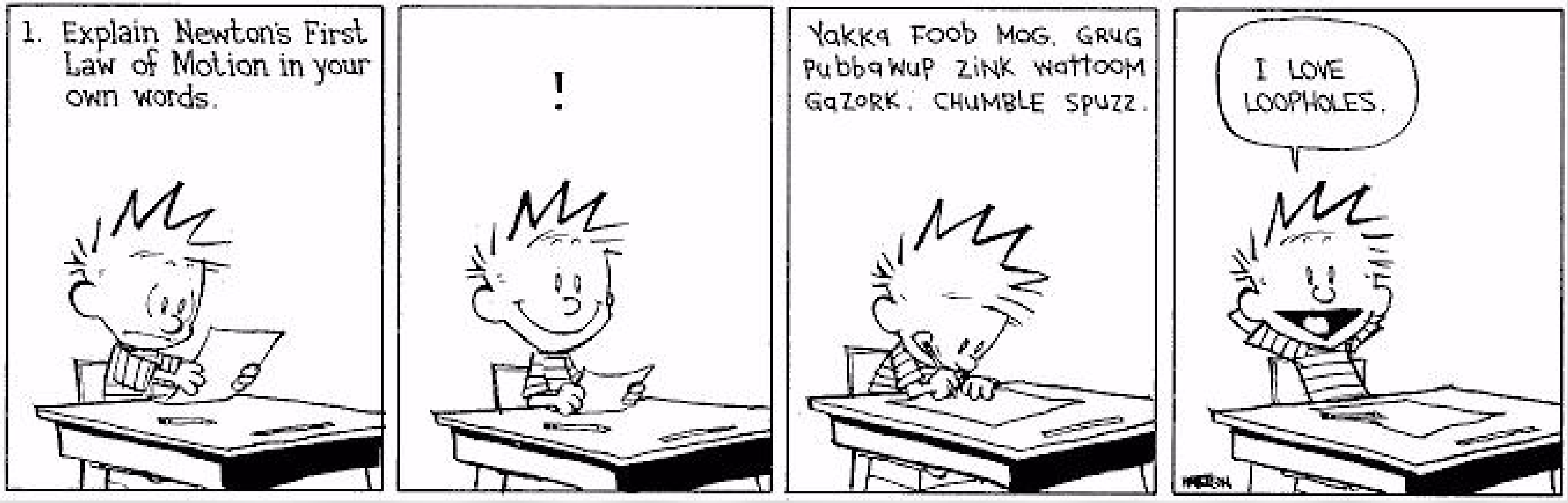
Return

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

$$where \quad dm<0$$

Physics is not math

- Physics includes math ...
  - But we don't hide behind it
  - Without a conceptual understanding, math is gibberish

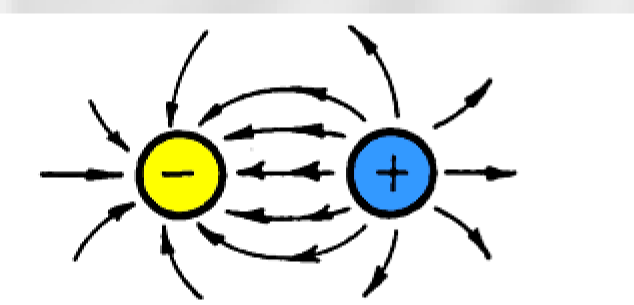


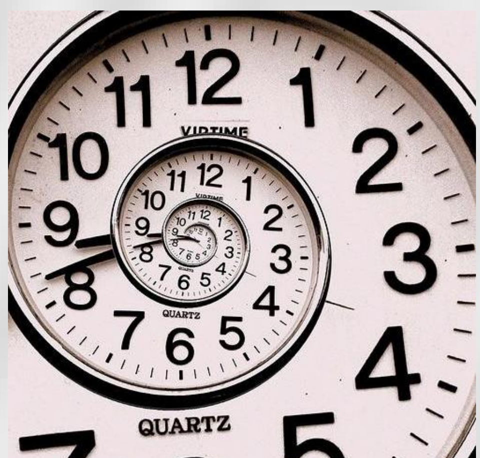
Fundamental (macroscopic) measurable quantities

- 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: ampere => coulomb, C

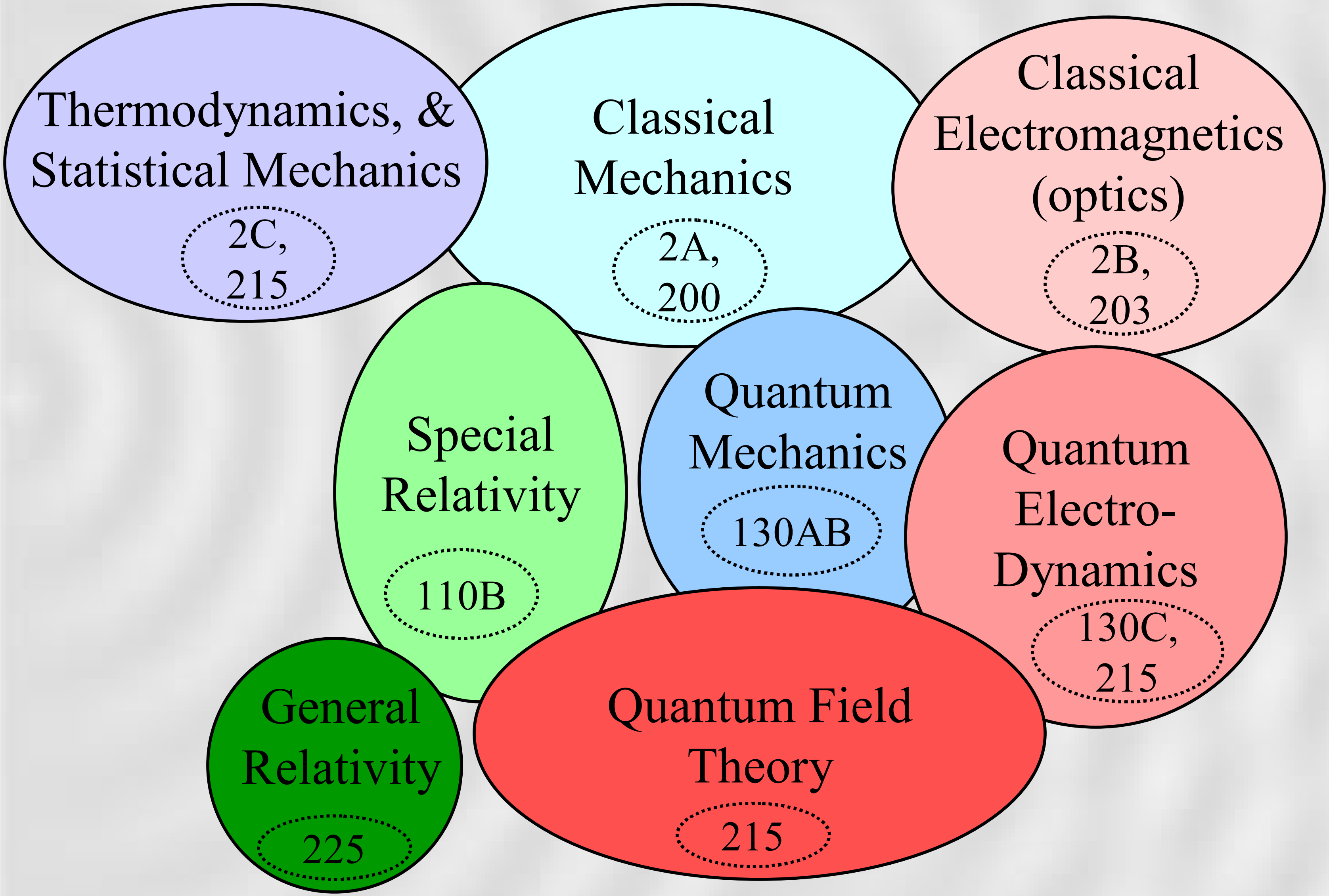




Science goals

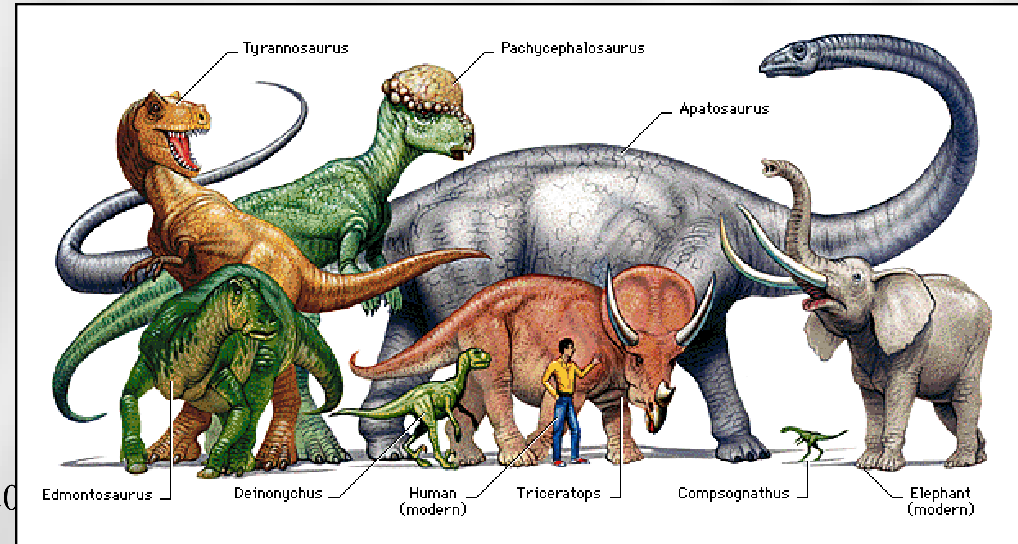
- "Now in the further development of science, we want more than just a formula.
  - First we have an observation,
  - Then we have numbers that we measure,
  - Then we have a law which summarizes all the numbers.
- But the real *glory* of science is that *we can find a way of thinking* such that the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

The pedagogical structure of physics



The language 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

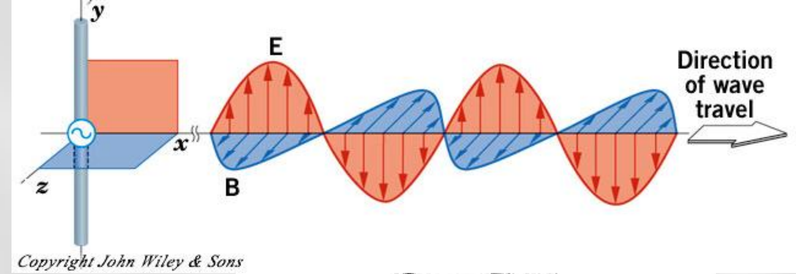


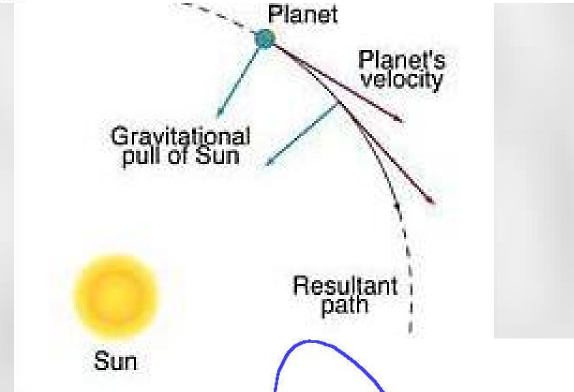
The language of science (2)

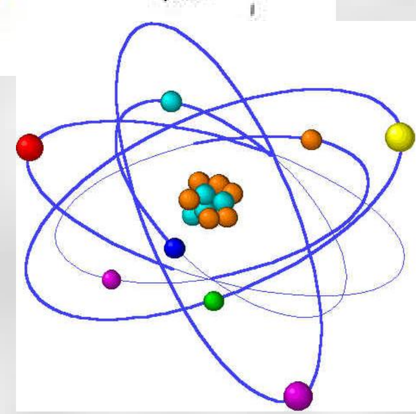
- **Fact**: A small piece of information
- Backed by solid evidence
  - In hard science, usually repeatable evidence
    - The sky is blue
    - Copper is a good conductor of electricity

- 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 language of science (3)

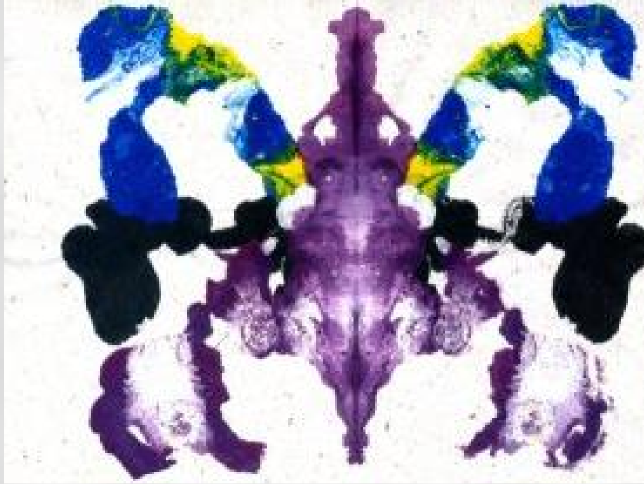




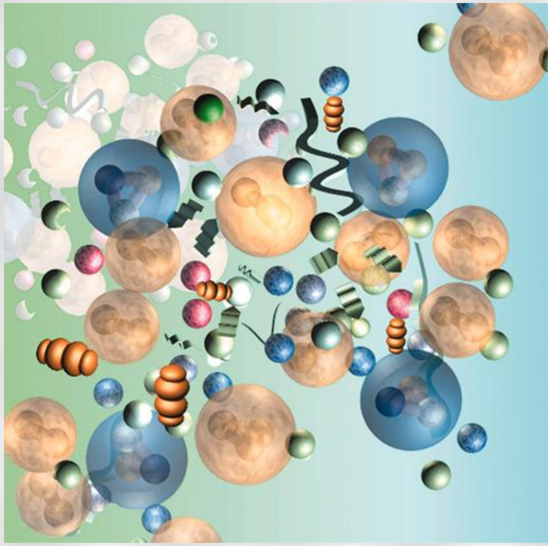


- **Theory**: The highest level of scientific achievement
  - A *quantitative, predictive, testable* model which unifies and relates a body of facts
  - Every scientific theory was, at one time, *not* generally accepted
  - A theory becomes accepted science *only* after being supported by overwhelming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

"Interpretations" are not science



- Asking "What is the meaning of the science?" is *not* a scientific question
  - Perhaps it is a philosophical question
- Interpretations are rooted, essentially by definition, in our everyday experience
  - 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 an "interpretation" of quantum mechanics
  - It is what it is: the most accurate physical theory ever developed
    - I don't have to like it

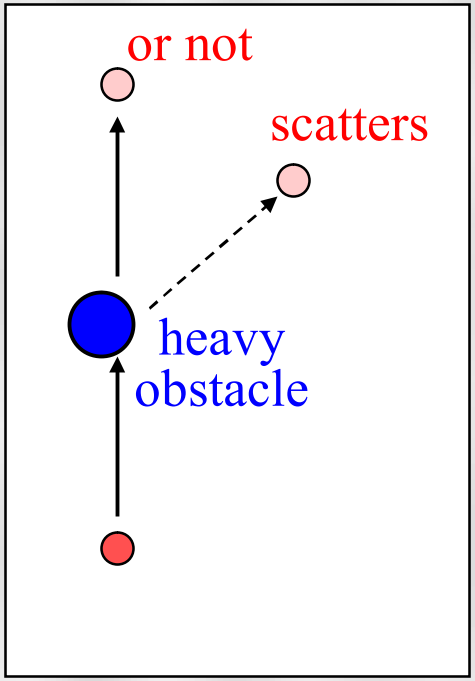
What is quantum mechanics?

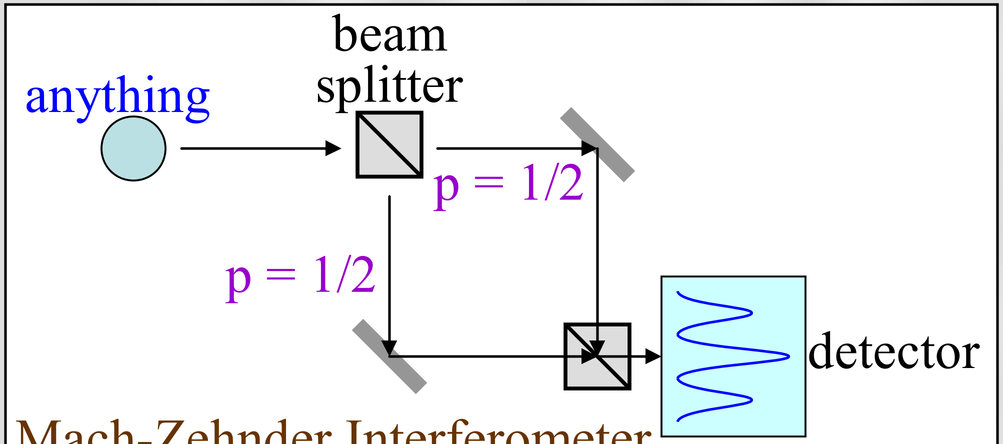
- Is it mystic?
- Or is it science?

It’s this one

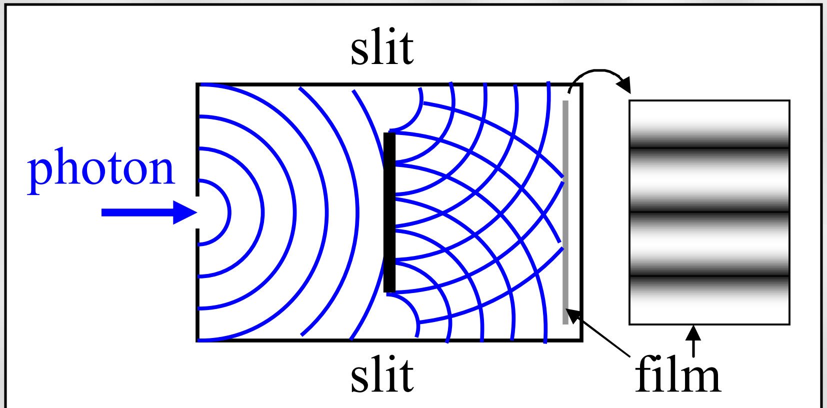
Reality is probabilistic

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





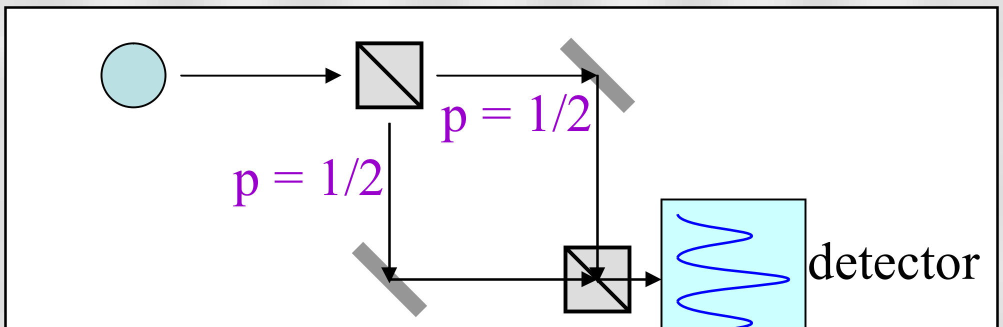
Mach-Zehnder Interferometer



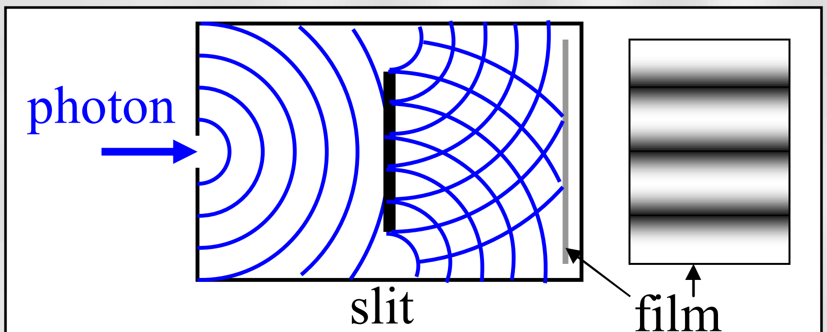
Double-slit (Young's experiment)

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.
  - Each component behaves as if it were the *whole* particle (whole mass, whole charge, whole spin, ...)
  - In the end, only one component is observed

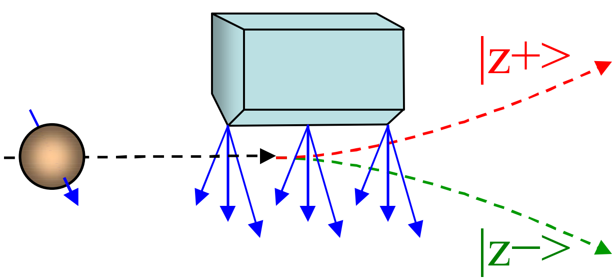


Mach-Zehnder Interferometer



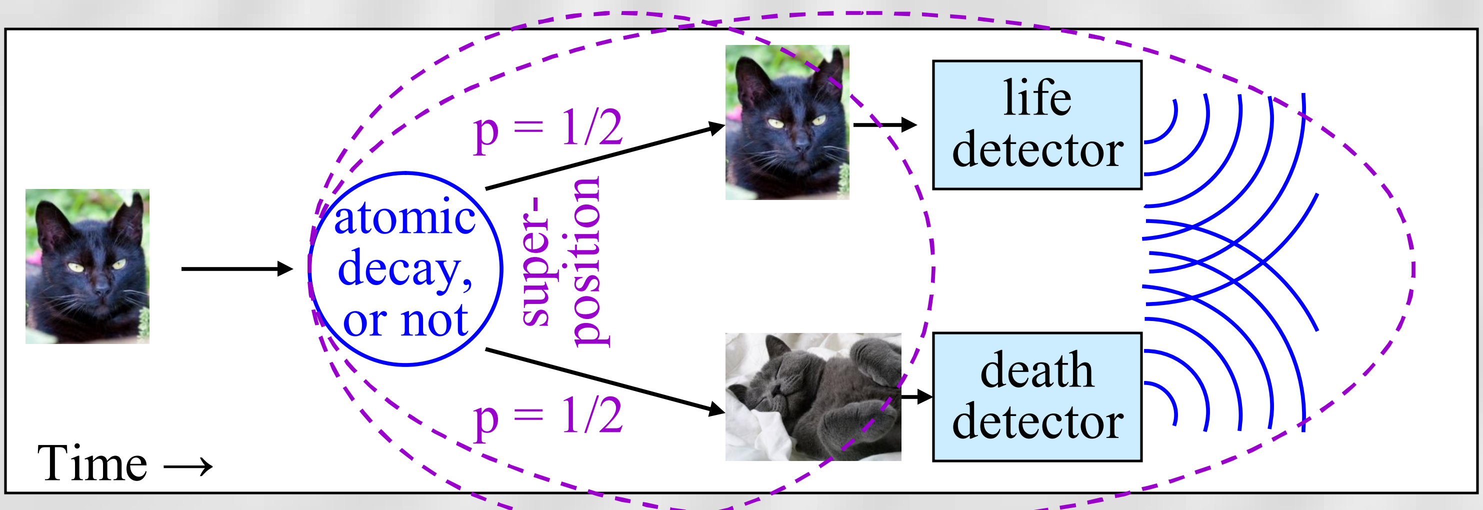
Double-slit (Young's experiment)

$$\left|x+\right\rangle = \frac{\left|z+\right\rangle + \left|z-\right\rangle}{\sqrt{2}}$$



What's up with that cat?

- Cat in a box, with an unstable atom rigged to poison
  - If the atom decays, the cat is dead
  - If the atom remains intact, the cat is alive
  - 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"
    - Implies the cat is in a superposition of dead and alive



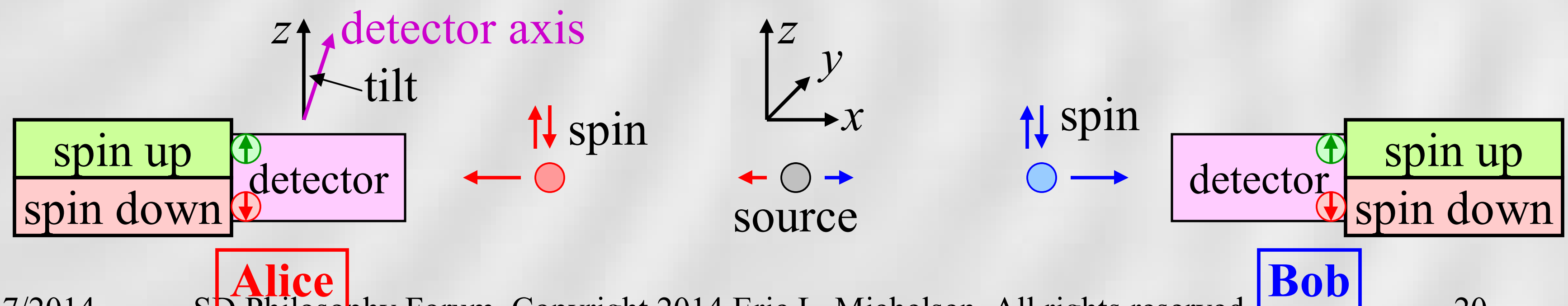
This is an example of entanglement

The "measurement problem"

- Why don't we ever measure superpositions?
  - What would that even mean?
  - We always measure definite values
- 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
  - What, exactly, is a "measurement"?

Entanglement

- A spin zero source emits 2 particles:
  - One is up (positive), the other is down (negative)
  - Alice & Bob each measure spin, & agree the sum is zero (every time)
- Alice's measuring device gets tilted, introducing an error
  - Therefore, sometimes their measurements are the same (both up or both down)
  - Now her device tilts 90° off: she is wrong ½ the time
- Now Bob's device also gets tilted: He is also wrong ½ the time
  - ¼ of the time, they're both right, + ¼ of the time, they're both wrong
  - 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, 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



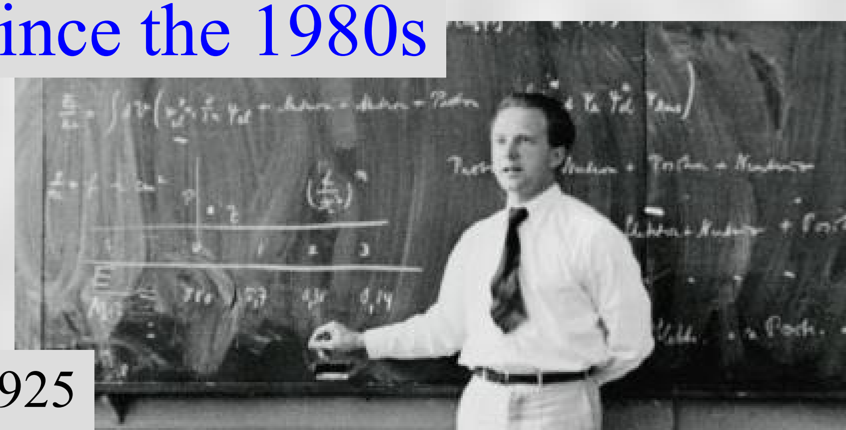
Decoherence: motivation

- Resolve the measurement problem
  - Where is the transition from quantum to classical?
    - No observed macroscopic superpositions
- What is a measurement?
  - I.e., when does the quantum state collapse?
    - Can a cat collapse it?

- This is now essentially resolved (as of 1980s)

It's time to bring QM into the modern era

- QM is ~90 years old
  - But it is still taught like the 1930s
  - Modern textbooks still ignore measurement theory
  - Worse, they still teach hand-wavy "collapse" without precise definitions
- A surprising amount of current *scientific* literature is devoted to "interpretations" of QM
  - A surprising 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
  - It's not that hard
    - For a quantum physicist, anyway



Heisenberg c. 1925

Decoherence overview

- The decoherence model explains everything from two principles:

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

quantum state

  - Time evolution, according to the Schrödinger Equation
  - “Mini-collapse” when a result is observed (by me!)

my words

- IMHO
  - Decoherence is the simplest, most intuitive QM model
    - Most consistent with other laws of physics
    - It is correct: It predicts the outcomes of experiments
  - Much of the literature discussion around decoherence is meaningless
    - “Decoherence is wrong because it contradicts my preconceived notions of what reality should be like.”

Interference is the hallmark of quantum mechanics

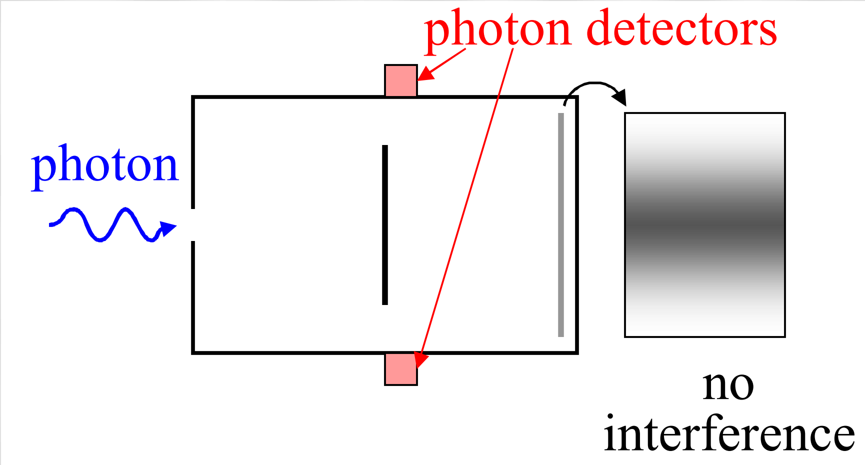
- If it interferes, it's quantum

  - If it doesn't, it's classical

- Quantum interference requires two things:
  - Recombining two components of the quantum state
  - Many "trials," possibly each of a single particle

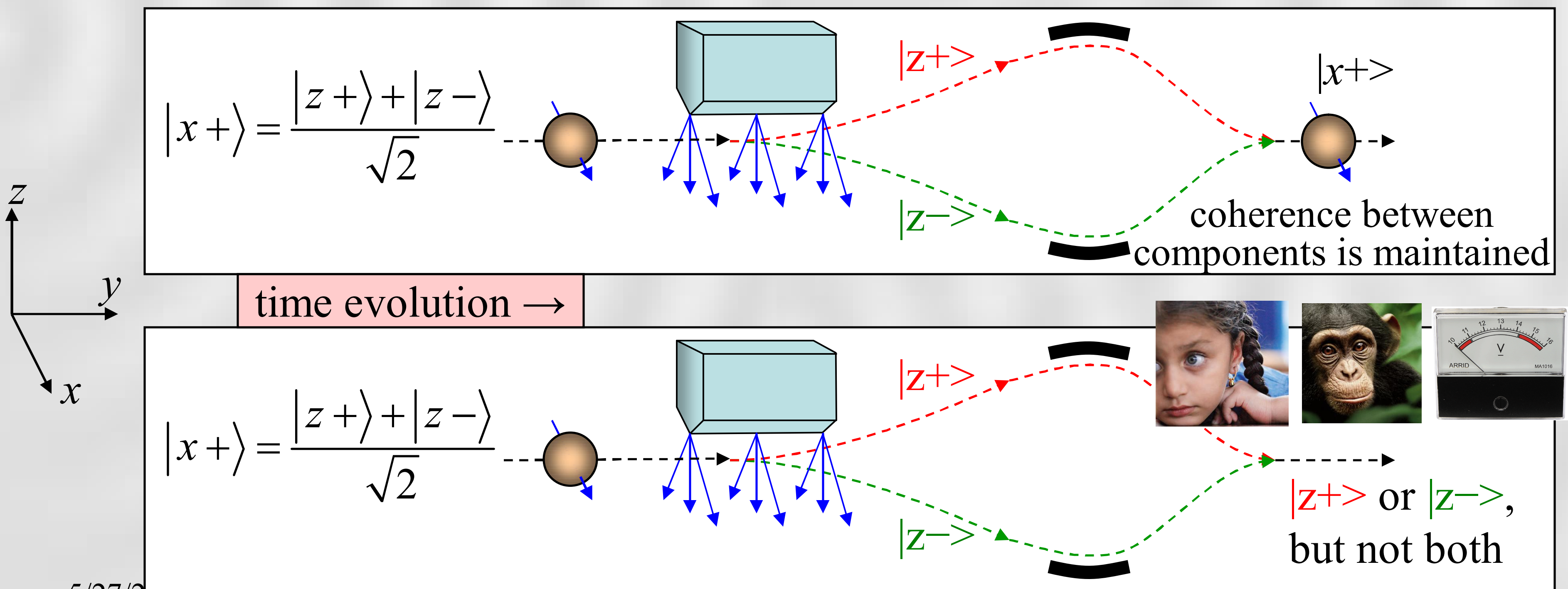
Which way did it go?

- If we try to see "which way" (welcher Weg) the photon went, we prevent interference
  - Only one photon detector triggers at a time
  - Suggests "complementarity:" it's either a wave, or a particle, but not both at the same time
    - But how does it know which to be?



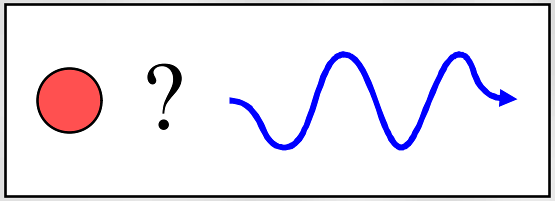
Aside: it's not just interference

- 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



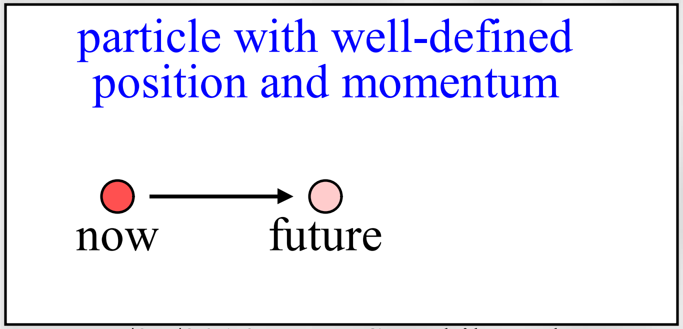
Ye olde complementarity (c. 1929)

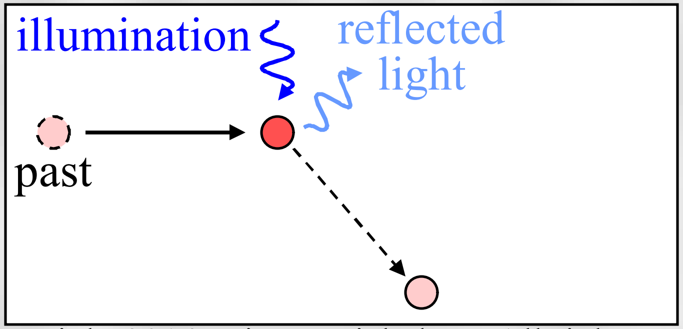
- Prevention of interference led to "Wave-particle duality," aka "complementarity"
  - Particles behave like either a wave or a particle, but not both
  - Which one depends on the experiment
- There are 4 completely different phenomena that have all been called examples of "complementarity"
  - Bohr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



(1) Bohr microscope

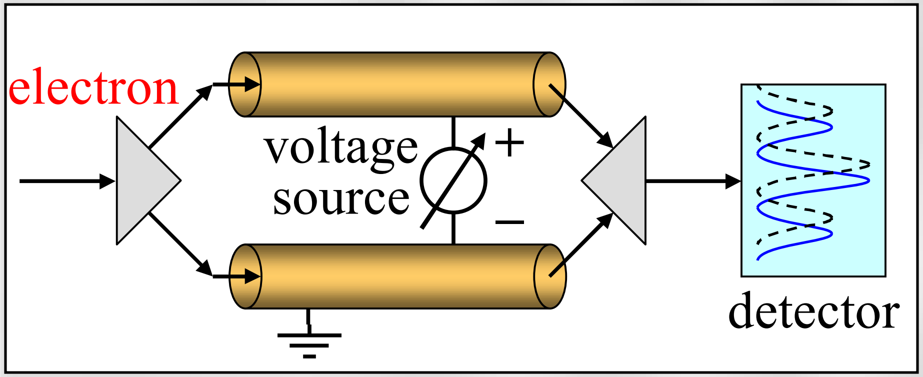
- Position-momentum uncertainty is from measurement clumsiness
  - Measurement “bumps” the particle out of a consistent state
  - Prevents an interference pattern
- I never liked this
  - Belies the nature of wave-functions
    - It’s not: a particle has a well-defined momentum and position, but nature 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.)

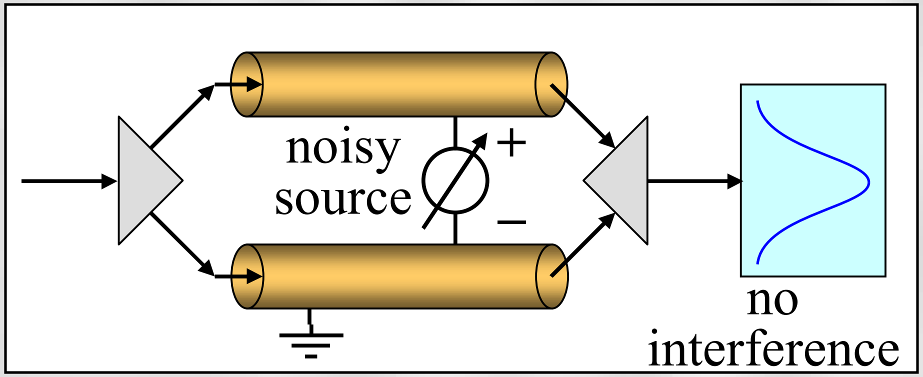




(2) "Fake" Decoherence

- 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

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

entanglement!

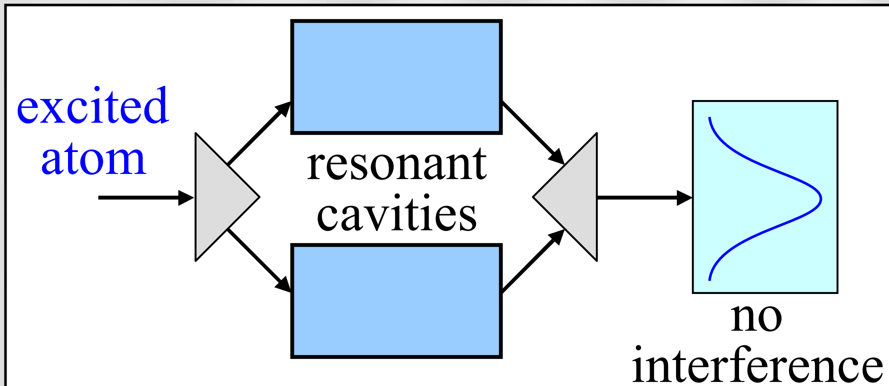
  - Is it a measurement?
  - Does it cause collapse?

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

interference terms

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

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



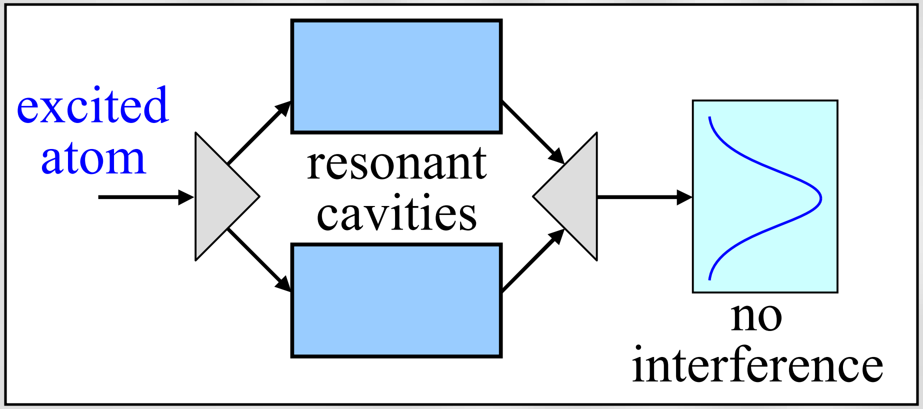
Scully, et. al., Nature, 351, 9-May-91, p111.

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

2. The non-overlap of the *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

What if the entangled states overlap (i.e., are *not* orthogonal)?

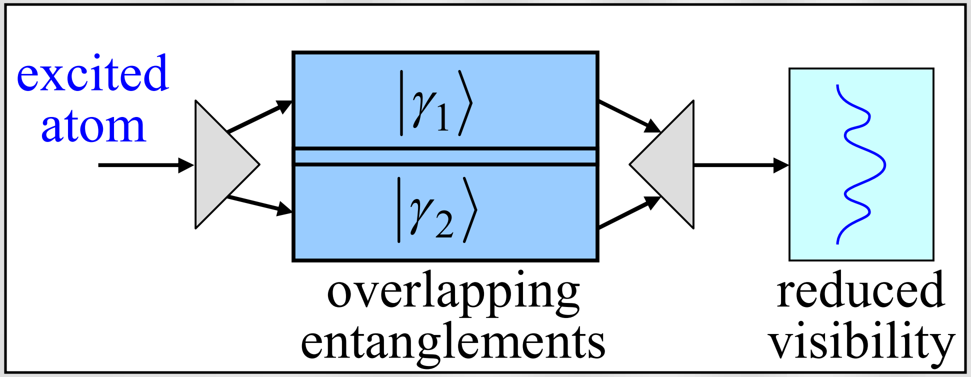
- Then interference is possible
  - With reduced visibility (smaller wiggles)

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

$$= \psi_{up}^*\psi_{up} + \boxed{\psi_{up}^*\psi_{dn}\left\langle\gamma_1\middle|\gamma_2\right\rangle + \psi_{dn}^*\psi_{up}\left\langle\gamma_2\middle|\gamma_1\right\rangle} + \psi_{dn}^*\psi_{dn}$$

$$\rightarrow \text{interference because } \left\langle\gamma_1\middle|\gamma_2\right\rangle = \left\langle\gamma_2\middle|\gamma_1\right\rangle \neq 0$$

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

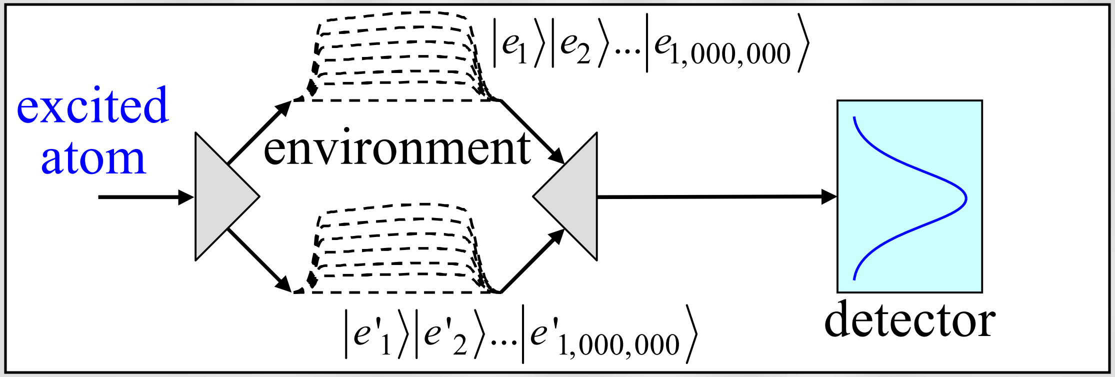


(4) "Real" decoherence

- The two components of the split particle interact with their macroscopic environment
  - Evolving through a cascade of progressively more entanglement with time
  - Even though the environmental states have significant overlap
    - The product of millions of numbers $< 1 \approx 0$

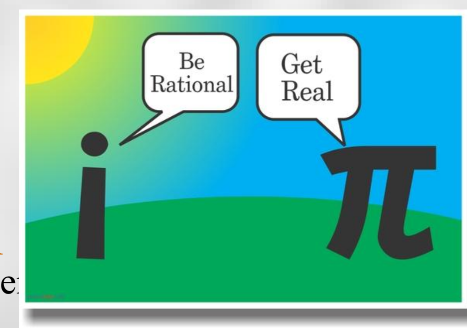
$$\psi = \psi_{up} + \psi_{dn} \to \psi_{up} |e_1\rangle |e_2\rangle \ldots |e_{1,000,000}\rangle + \psi_{dn} |e'_1\rangle |e'_2\rangle \ldots |e'_{1,000,000}\rangle$$

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

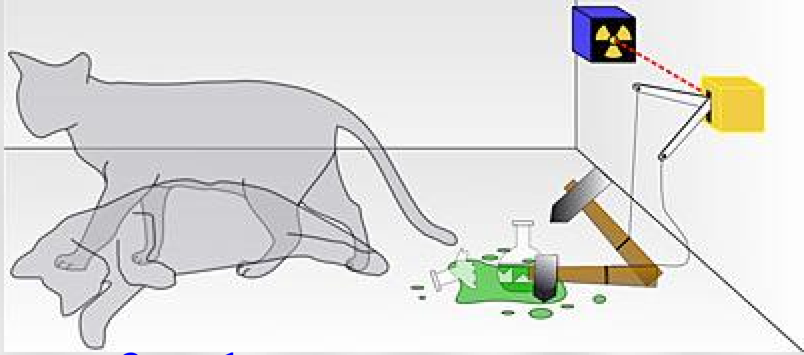


“Real” decoherence: why we don’t measure superpositions

- Real experiments are inevitably connected to their surrounding environment
- Macroscopic ones are connected to billions of particles (“subsystems”) in the environment
  - This means they decohere on extremely short timescales, $\sim 10^{-18}$ 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 only “weird” phenomenon of quantum mechanics
    - The rest is just a deterministic time evolution of the quantum state according to the Schrödinger equation



Total loss of coherence is equivalent to collapse



- It doesn't matter what causes loss of coherence (fake or real decoherence)
- 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 collapse model has problems:
  - Cannot explain partial coherence (i.e., reduced visibility)
    - Collapse is binary: it happens or it doesn't
    - Decoherence is continuous: relative phase of components becomes smoothly more statistically diverse
    - Interference visibility smoothly drops to zero

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 physical model *must* defer the collapse to the last possible moment
    - All other time evolution simply follows the Schrodinger equation

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

Observers are macroscopic

- When I look at a measurement device, my macroscopic body totally decoheres the possible measurement outcomes long before my brain can interpret the results
- Therefore, the decoherence model implies that "mini-collapse" can occur only *after* total decoherence
  - I.e., 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
  - It is fully consistent with partial coherence

The role of the observer

- 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
    - 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.
- I don't think "interpretations" of QM have any scientific basis
  - Angels on the head of a pin

Is quantum uncertainty an opening for free will?

- As a scientist, I don't talk about this much
  - 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