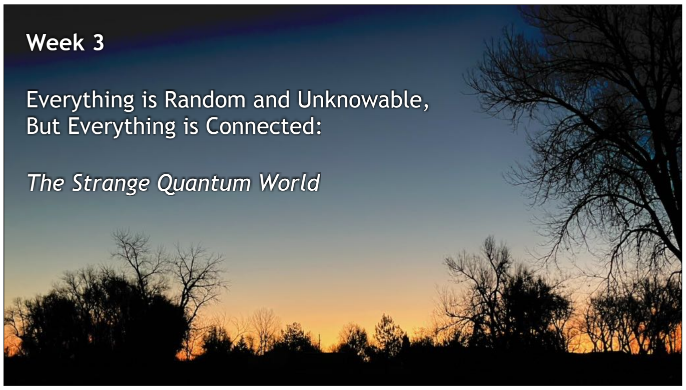
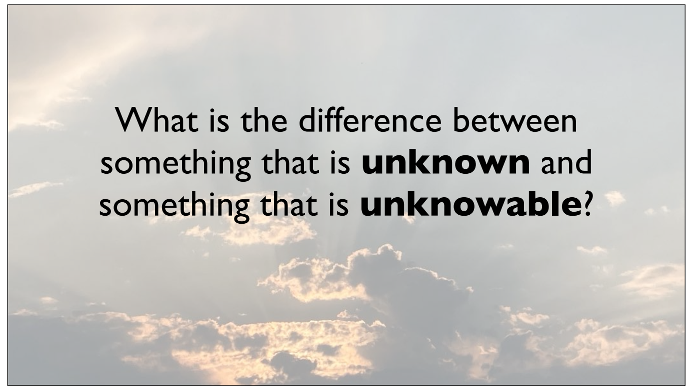
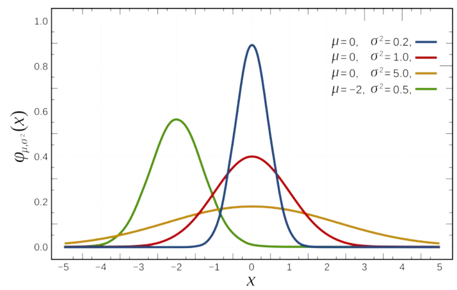




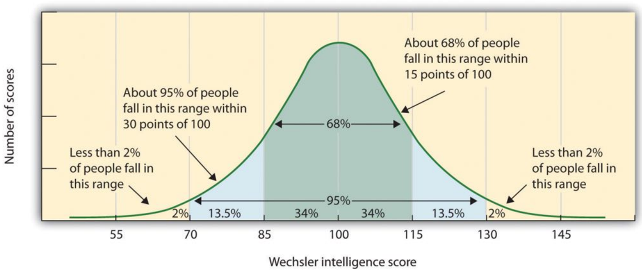
Your height varies over the day. How accurately do you think you can know your height? We use the symbol Δ to denote uncertainty.

$\Delta h = ?$

Normal Distribution



Normal Distribution

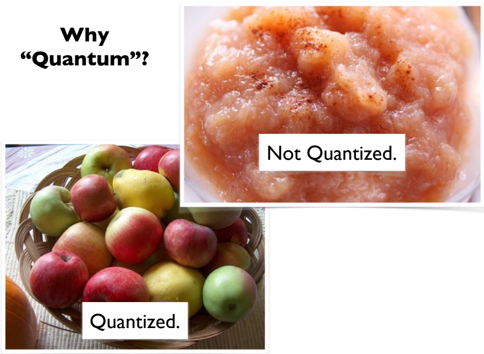


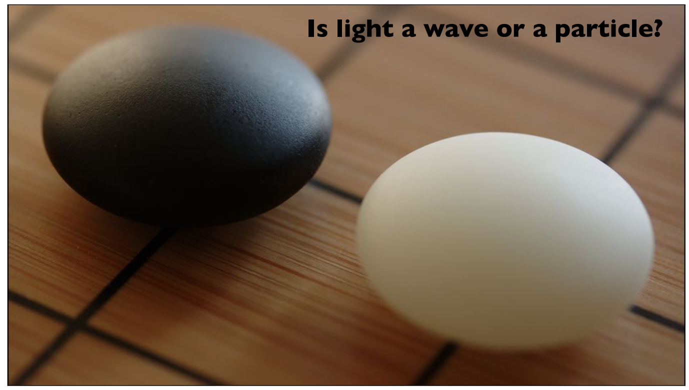
Reasoning with Equations

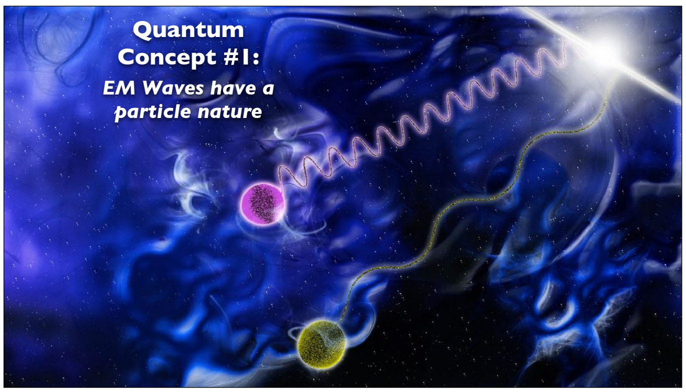
$$c = f\lambda$$

Red light has a longer wavelength than blue light. Which color has a higher frequency?

Why "Quantum"?

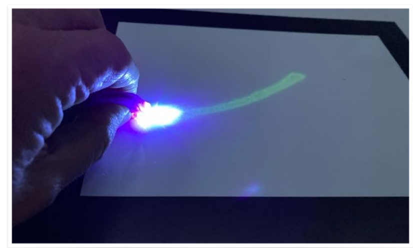






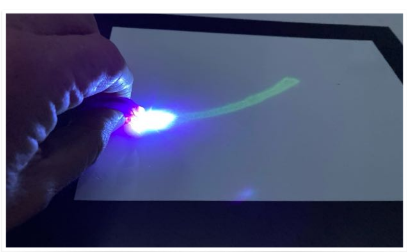
Writing with Light

Touch (gently!) different color flashlights to the glow-in-the-dark surface. Which colors leave trails?



Writing with Light

Light comes in "chunks" of a certain size related to the wavelength.



Which has higher energy?

Red light photons

Blue light photons

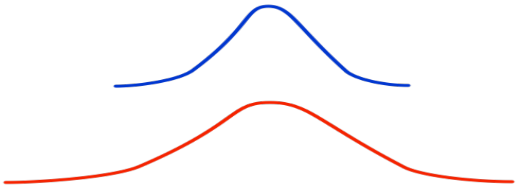
Which has higher energy?

Red light photons
Long wavelength
Low energy

Blue light photons
Short wavelength
High energy

Photons Look Like Particles

Where Is A Photon?

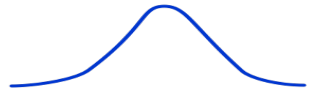


Which can you locate more precisely?

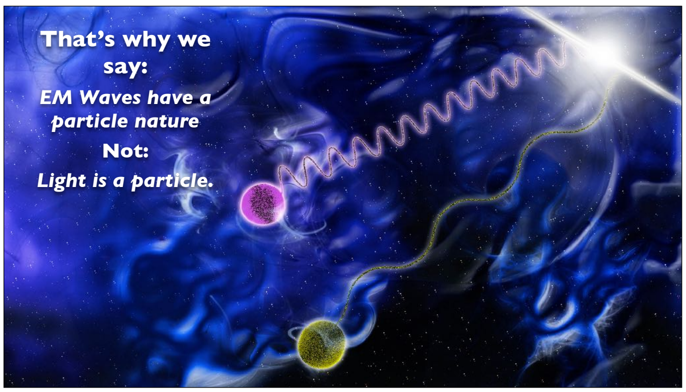
Worth Knowing:

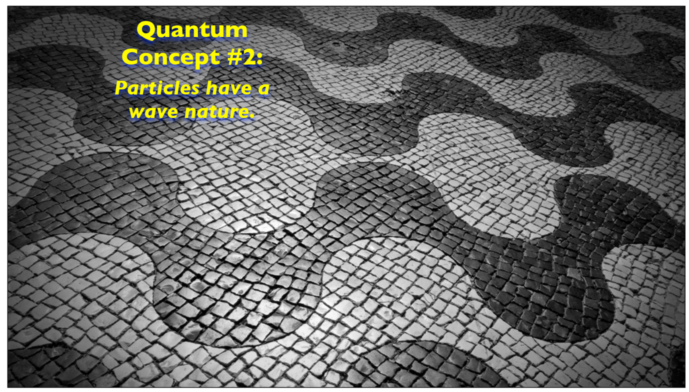
Quantum Waves Aren't Like Other Waves.

Before the photon hits the screen.

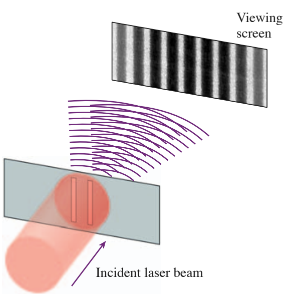


After the photon hits the screen.

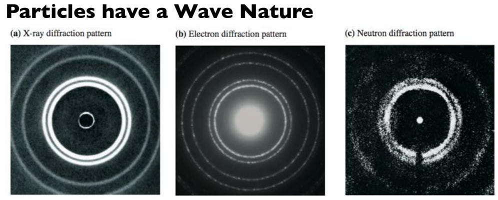




Double Slit Interference Pattern



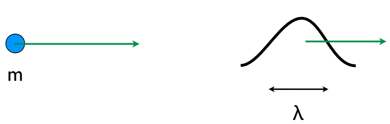
Particles have a Wave Nature



$$\lambda = \frac{h}{p} = \frac{h}{mv}$$

De Broglie wavelength for a moving particle

This doesn't matter for macroscopic objects.

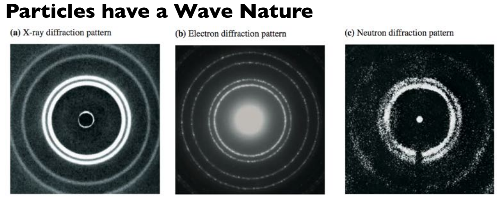


Localized. Smeared out.

Wavelength of a squirrel running at 3 m/s:

1×10^{-33} m

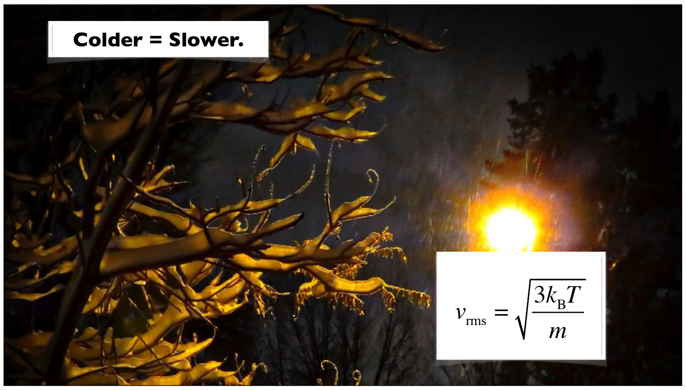
Particles have a Wave Nature

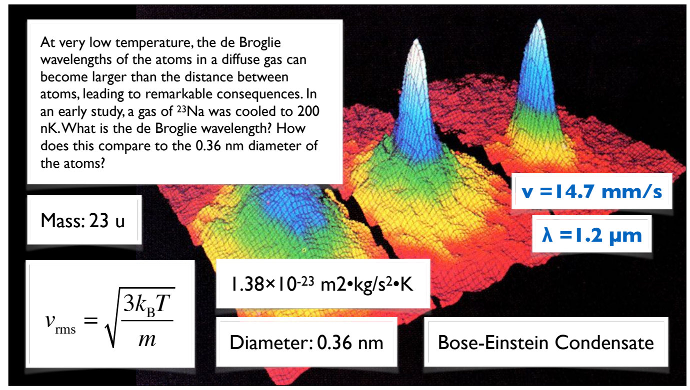


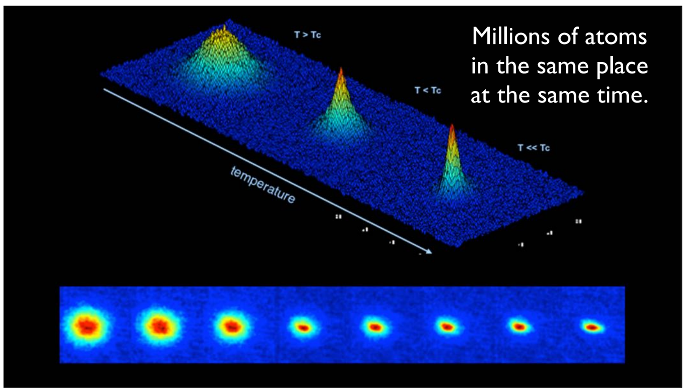
$$\lambda = \frac{h}{p} = \frac{h}{mv}$$

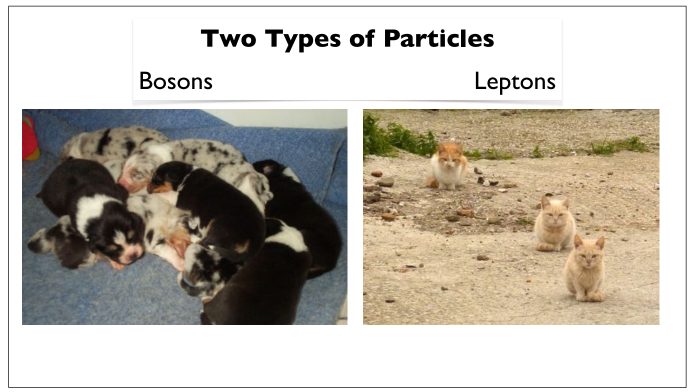
De Broglie wavelength for a moving particle

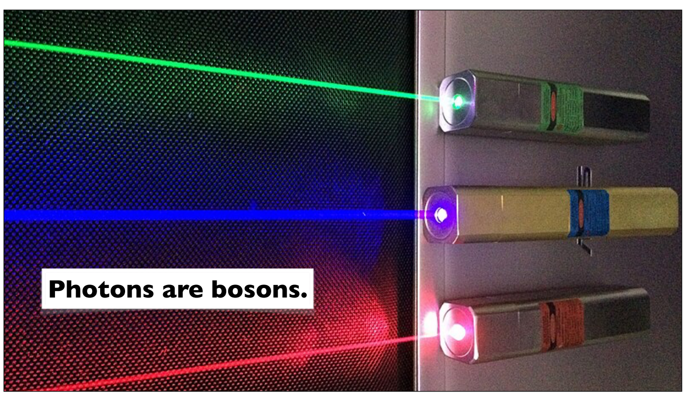
If a particle slows down, how does its wavelength change?

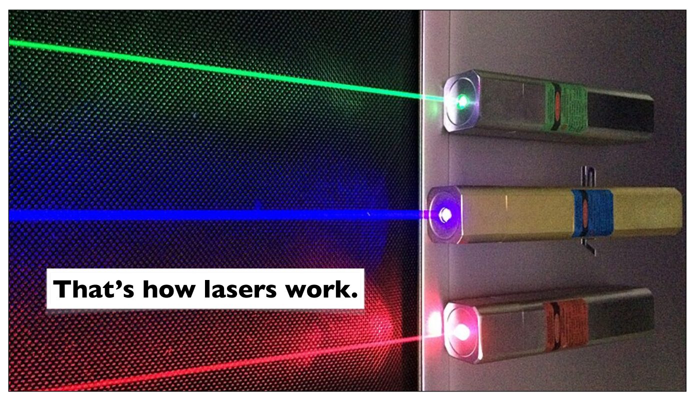

Colder = Slower.
$v_{rms} = \sqrt{\frac{3k_B T}{m}}$

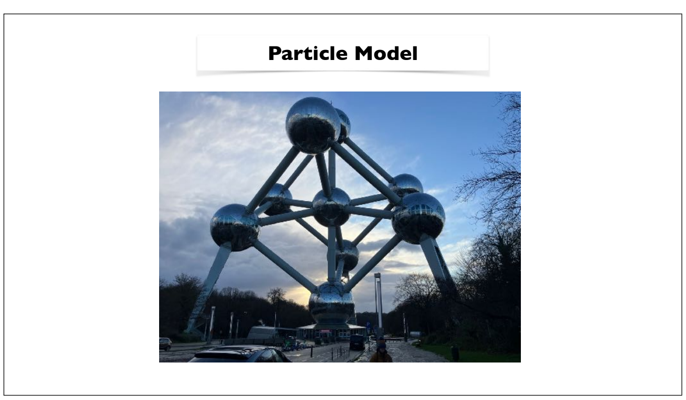

At very low temperature, the de Broglie wavelengths of the atoms in a diffuse gas can become larger than the distance between atoms, leading to remarkable consequences. In an early study, a gas of ^{23}Na was cooled to 200 nK. What is the de Broglie wavelength? How does this compare to the 0.36 nm diameter of the atoms?
v =14.7 mm/s
λ =1.2 μm
Mass: 23 u
$v_{rms} = \sqrt{\frac{3k_B T}{m}}$
1.38×10^{-23} m2•kg/s^2•K
Diameter: 0.36 nm
Bose-Einstein Condensate

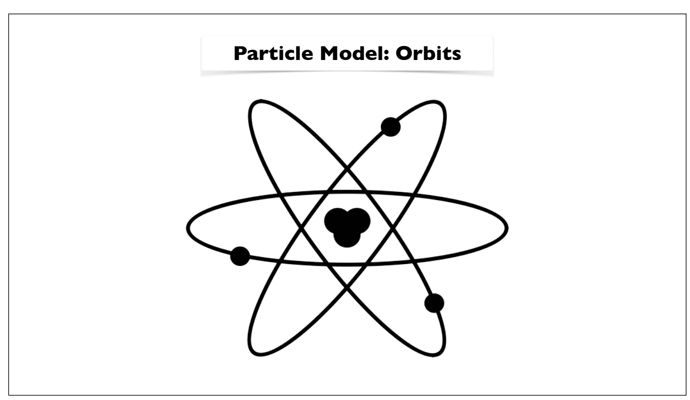

Millions of atoms in the same place at the same time.
T > Tc
T < Tc
T << Tc
temperature


Two Types of Particles
Bosons
Leptons

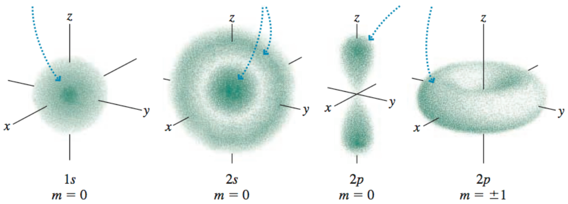

Photons are bosons.


That's how lasers work.

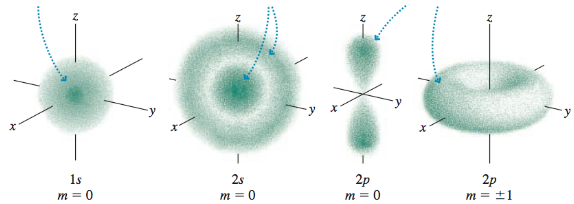

Particle Model


Particle Model: Orbits

Wave Model: Orbitals



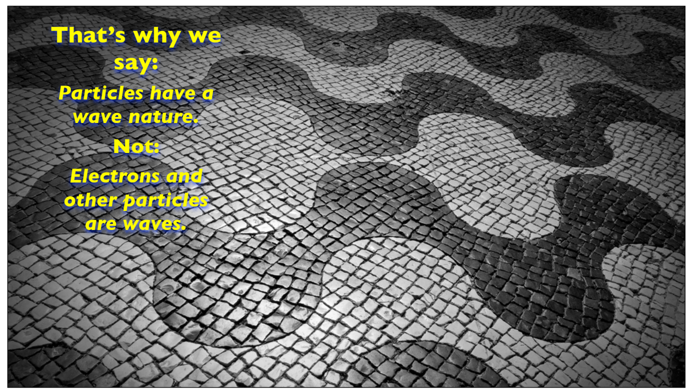
Wave Functions

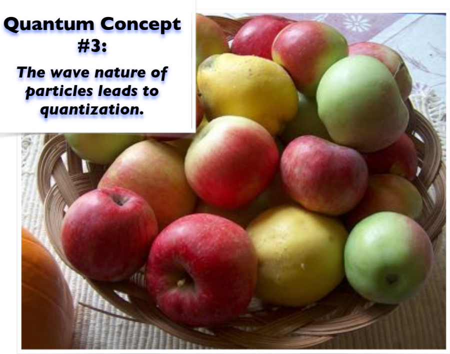


But when the waves hit the screen....

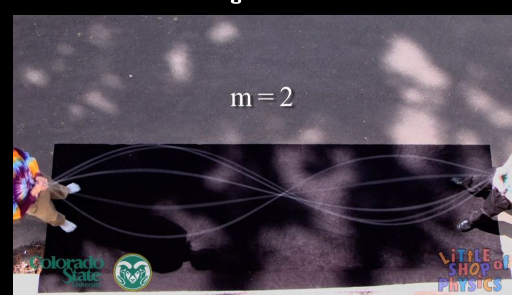
(c) Neutron diffraction pattern

…they look like particles.



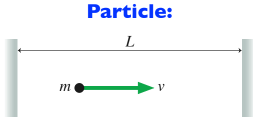


Standing Wave Modes

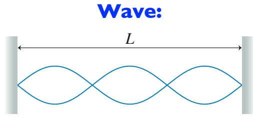


Particles have a wave nature. So...

Particle:

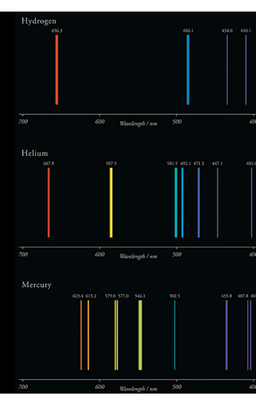


Wave:



...the possible states are **quantized.**

Line Spectra



The Crux of the Quantum Biscuit

Photons have a particle nature.

↓

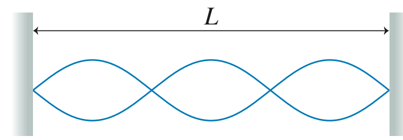
Their energy is quantized.
It comes in chunks of a particular size.

Particles have a wave nature. Confining them restricts them to certain energy states.

↓

The energy of a confined particle is quantized.
It is restricted to certain values.

When you constrain a wave, it can only have certain states.



$$E_n = \frac{1}{2m}\left[\frac{hn}{2L}\right]^2 = \frac{h^2}{8mL^2}n^2 \qquad n = 1,2,3,4...$$

Allowed energies for particle in a box

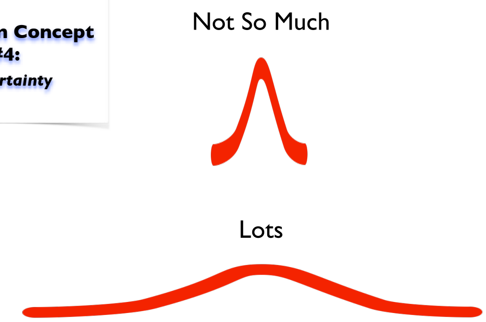
What happens when you change the box size?

$$E_n = \frac{1}{2m}\left[\frac{hn}{2L}\right]^2 = \frac{h^2}{8mL^2}n^2 \qquad n = 1,2,3,4...$$

Allowed energies for particle in a box

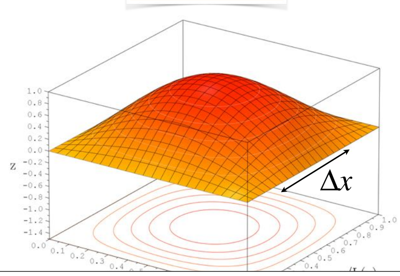
If you make the box smaller (make *L* smaller), how does that change the energies?

Quantum Concept #4:
Uncertainty



Heisenberg uncertainty principle

$$\Delta x \, \Delta p_x \geq \frac{h}{4\pi}$$

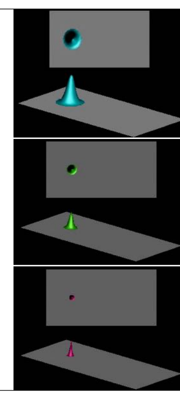


Uncertainty

If I know where you are, I don't know where you are going.

$$\Delta v \propto \frac{1}{\Delta x}$$

Δx large



Δx small

Everything is in Motion

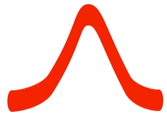
Can I say that something is not moving?

Quantum Zero Point Energy

Things are moving, even at absolute zero.

What does the wave function *mean?*

Before Measurement:

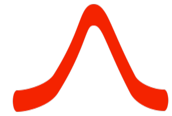


After Measurement:

The wave function is the particle.

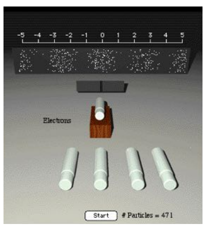
It behaves differently depending on circumstances.

Before Measurement:

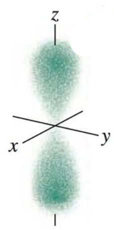


After Measurement:

Quantum Weirdness #1: Non-locality



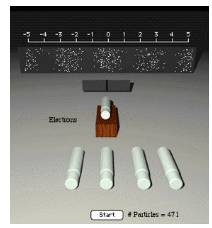
Which slit did the electron go through?



$2p$
$m = 0$

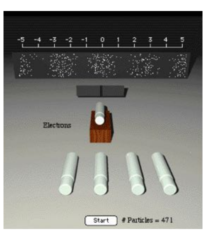
Where is the electron?

Quantum Weirdness #2: Unknowability

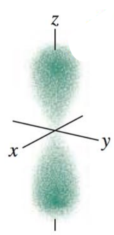


If you know which slit the electron goes through, it changes the pattern.

Related Concept: Measuring Reality Affects Reality



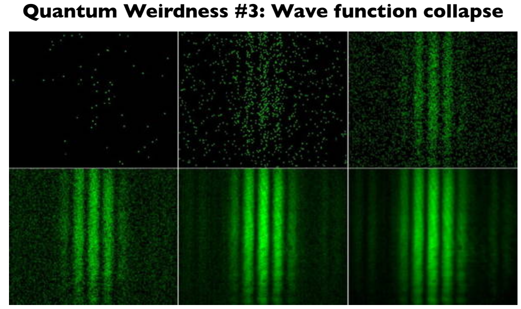
Which slit did the electron go through?



$2p$
$m = 0$

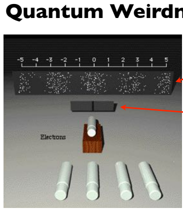
Where is the electron?

Quantum Weirdness #3: Wave function collapse



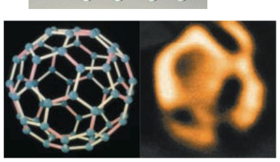
Single-photon diffraction pattern

Quantum Weirdness #4: Duality



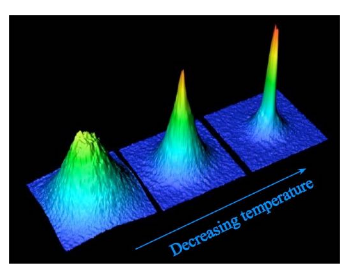
Acting like a particle

Acting like a wave



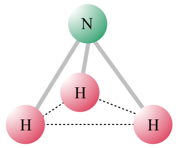
Buckyball:
Looks like particles
Can act like a wave

Quantum Weirdness #5: Superposition



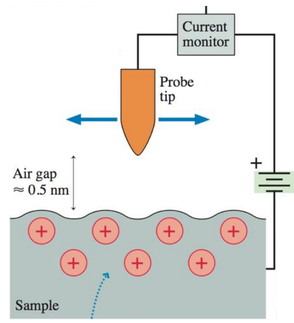
Bose-Einstein Condensate

Quantum Weirdness #6: Tunneling

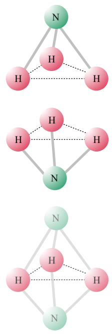


Transition
between
states

Scanning Tunneling Microscope



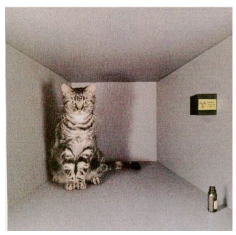
Quantum Weirdness #7: Mixed States



Up

Down

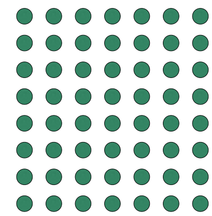
Up
and
Down



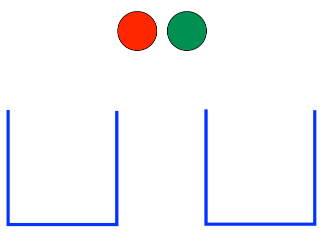
Schrödinger's Cat

Quantum Weirdness #8: Indistinguishability

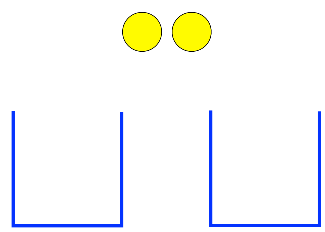
Identical.



Indistinguishable.

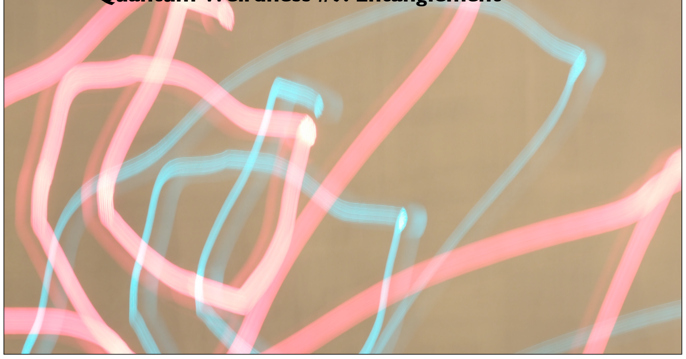


How many ways to arrange the
two balls in the two containers?

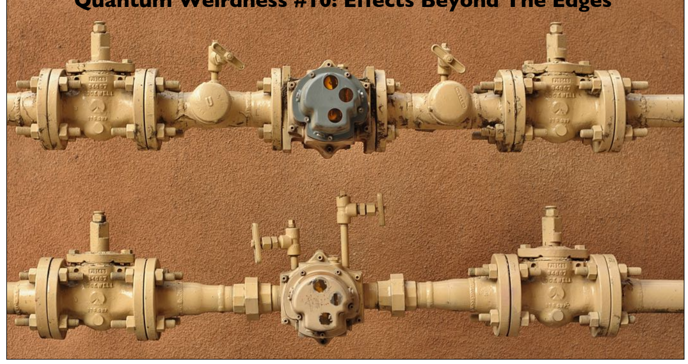


How many ways to arrange the two
electrons in the two containers?

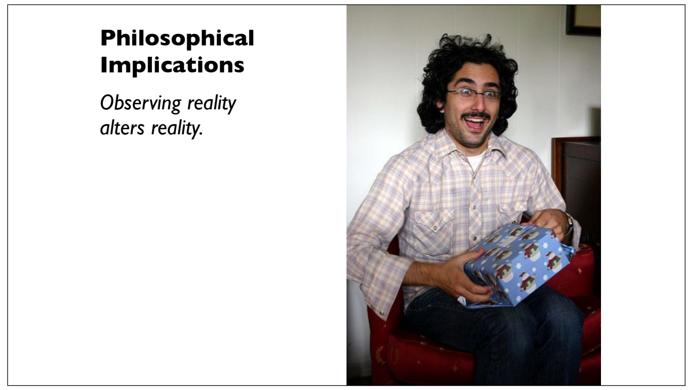
Quantum Weirdness #9: Entanglement

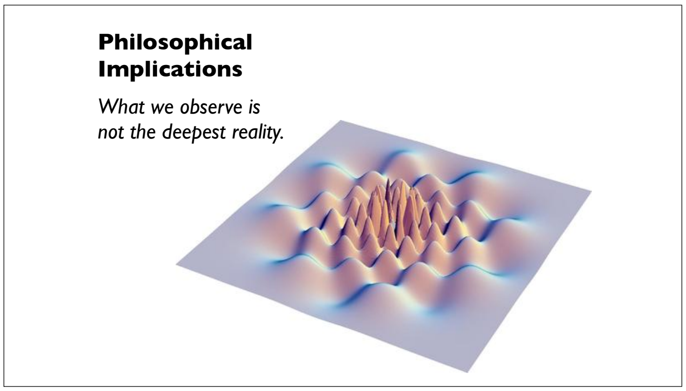


Quantum Weirdness #10: Effects Beyond The Edges

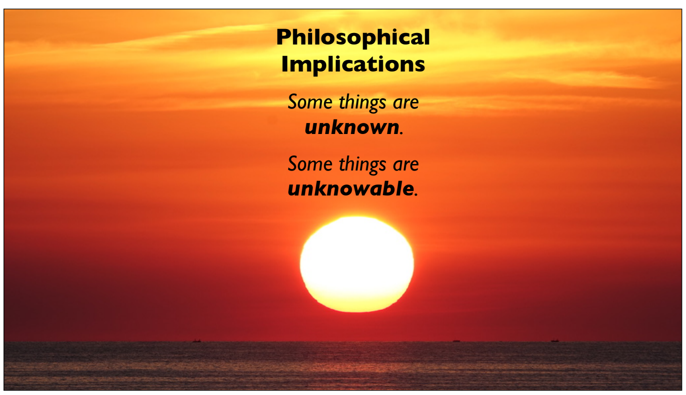


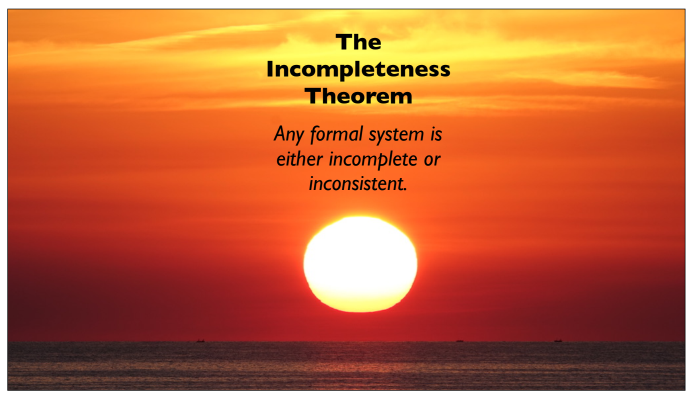

Philosophical Implications
EVERYTHING IS CONNECTED

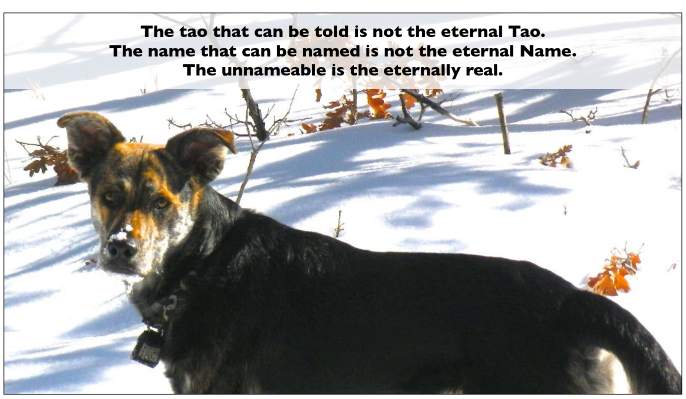

Philosophical Implications
Observing reality alters reality.


Philosophical Implications
What we observe is not the deepest reality.


Philosophical Implications
We can only speak about what we can observe.


Philosophical Implications
Some things are **unknown**.
Some things are **unknowable**.


The Incompleteness Theorem
Any formal system is either incomplete or inconsistent.

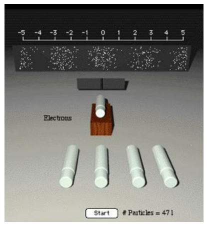

The tao that can be told is not the eternal Tao.
The name that can be named is not the eternal Name.
The unnameable is the eternally real.


If a tree falls in the forest...

Philosophical Implications

Some things are not just ***unknown.***

They are ***unknowable.***



Which slit did the electron go through?