Quantum Mechanics:
Stranger than we can imagine?
In which we make two points:

1. No local realist picture of the world can agree with data.

2. Nature hints that there are many outcomes to every process.
Chronology

1900: Kelvin says physics was solved except for two clouds on the horizon. One led to relativity, the other to quantum mechanics.

1900: Planck: light behaves as if it arrives in lumps, not as continuous waves.

1905: Einstein proposed taking that lumpiness seriously.

1912: Debye shows that sound is lumpy like light.

1913: Bohr proposes that similar lumpiness accounts for the structure of atoms.

1921: A. C. Lunn (U. Chicago) proposes a wave theory and solves it for the hydrogen atom. Rejected by Physical Review.

1923: DeBroglie wave picture of particles. (same as Lunn’s)

1925: Schroedinger wave equation (same as Lunn’s)

Gradually, the old Newtonian physics of the microscopic world (atoms, molecules,...) was entirely replaced by a new theory, quantum mechanics. Now ALL our understanding of materials properties (chemistry, conductivity, springiness,...) is based in QM.

So this ‘new’ physics is older than almost every one in this room. Maybe it’s time to try to look at its implications.
Particle-Waves Through Slits

Quantum interference experiments with large molecules

- Little $C_{60}$ soccer-balls are shot through some slits.
- They arrive one at a time at a detector.
- They show wave interference.
- Do they really go through all the slits at once?
Quantum Randomness

• Let’s listen to a quantum process: a Geiger counter. Who hears the pattern in the clicks?
  – Let’s listen again.
    – We can’t predict exactly when the next click will come.

• Before we go on, let's be clear:
  QM does NOT say "everything is uncertain."

• Here's a number from a standard table:
  – Planck’s constant (the ratio of energy lump size to wave frequency) is
    \[ h = 6.6260755 \pm 0.000004 \times 10^{-34} \text{ J-s}. \]
  – So even if we find that some things are unpredictable, we’re NOT saying that
    ‘everything’ is too fuzzy to describe.
Does God play dice with the universe?

- Are those clicks really at purely random times? Or are the causes, hidden away, as in many familiar ‘random’ events?

- How can you test if there are hidden little causes or just purely random events? Not impossible: in 1964 John Bell figured out a way to test whether events have anything like ‘causes’.

- Let’s start by applying Bell’s test to something we can picture, not to little particle/waves.
A Science Fiction Story

Say that you want to find out why people like pepperoni, mushrooms, and olives on pizza.

You ask many people, and they give Yes/No answers when asked about each. (Say 50% yes for each.)

But you don't notice any distinguishing properties of the people who say Y. Does that mean you can conclude that the answer is random, some sort of momentary glitch that occurs in a person's response?

Of course not- you may just have missed the "hidden variables" needed to understand taste. There MAY be something in each person's mind ahead of time that determines their answer, or maybe not.
Testing Random vs. Causal?

• Try asking *couples*. Each couple gives the *same answer* to the one question you ask them, So there was already something in their heads that determined the answer. How else could they all get their stories straight?

  There's a slight complication- all these folks seem to get confused after one question. If you ask each member of the couples a second question, the perfect correlation between them is lost. So you're only allowed to ask one of each person.

• Now try asking one person about pepperoni, and the other about mushrooms. ~85% of the time, they give the same answer (YY or NN).

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So you conclude that whatever makes people like mushrooms usually makes them like pepperoni. You try the same thing asking about mushrooms and olives. Again ~85% of the time, they give the same answer.
Three Questions
Now you ask about pepperoni and olives. What extent of agreement do you expect?

The 15% of couples who had different opinions on M-P and the 15% with different opinions on M-O might all be different people. Then there’d be 15% + 15% = 30% disagreement on P-O.

Or maybe they're all the same people. Then there’s 0% disagreement on P-O.

It could come out anywhere in between 0% and 30%.

What do you find?
They disagree 50% of the time!

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• Try to fill that M row in with Y,N that’s 85% the same as BOTH the O and P rows!
  – Not possible.

• We claim there really are answers to each question, because when we ask the same question of each person we get the SAME answer.

• Yet there’s no way to fill in all three rows with answers that meet the % agreements that we find between rows.
What gives?

• Maybe there was a statistical fluke. Try again with 100,000 couples.
  – Same result.

• Maybe the couples were secretly signaling each other, getting their stories coordinated (on some questions) AFTER the questions were asked. You ask the questions in sealed boxes.
  – Same result.

• You ask the questions SIMULTANEOUSLY (in Earth frame).
  – Same result.

• Maybe the couples were getting their stories straight only on the questions which they knew they would be asked. (Animal House?) The lists of answers only exist for those questions, not the ones that won’t get asked. So you draw the questions out of hats, in the sealed boxes, simultaneously.
  – Same result.

• Then if only TWO answers exist for any pair, there would have to be a conspiracy between the couples and whoever sets the ‘randomly chosen’ pair of questions.
Now tell exactly the same story about particles of light, where "couples" are pairs emitted together in a decay process.

- "Like pepperoni?" -> “polarized vertically?”
- "Like olives?" -> "polarized 45° from vertical?"
- “Like mushrooms?” -> "polarized at 22.5° from vertical?"
  • You don’t have to know what those variables mean- just that each leads to clicks on a detector if the answer is yes!

- Experimentally the results are as we have described.

- Even though we always get agreement when we ask the same question of each partner, there CANNOT be lists of what those answers would be before we ask. You can’t have two lists each almost the same as the third, but very different from each other!
We assumed something false when we concluded that this story must be science fiction.

• What did we assume about reality?
  – Note that we assumed nothing whatever about QM - we didn't even mention it.
  – It happens that QM precisely predicts the results, but we are now finding how the world differs from our assumptions, not how quantum theory differs from our assumptions.
We assumed

- **Realism.** The world may or may not be random, but those parts of it which can be perfectly predicted have some real cause.
  - "If, without in any way disturbing a system, we can predict with certainty (i.e., probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity."
    – (Einstein, Podolsky, Rosen, 1935)

- **Causes are local.** You can’t change the outcome here by doing something over there unless there’s time for some signal to travel.

- **No conspiracies.** Nobody handed out instructions ahead of time to the little random particles *and* the little random, question choosers, telling them exactly what to do to mess with our heads.

Which one are you willing to give up?
What Gives?

• We don’t know, but we do conclude that the universe has features that are not describable as results of pieces moving around in space and time. Somehow it knows the linkage between two distant results without knowing either of those results! (Here I’m assuming no conspiracies.)

• So while you’re getting used to that:
  What does the quantum picture say about where the randomness comes in?
The Quantum Rules

- The physical state of a system is described by a ‘quantum state’
  - in simple cases, a wave.
  - Let’s call it $\psi(r,t)$

- There’s an equation (Schroedinger's) that says how that state changes in time, just like Newton’s laws say how a classical state changes in time:

$$i\frac{\hbar}{h} \frac{d\psi(\vec{r}, t)}{dt} = -\frac{\hbar^2}{2m} \nabla^2 \psi(\vec{r}, t) + V(\vec{r}, t)\psi(\vec{r}, t)$$

- There are only two things you need to know about that equation:
  - 1. It’s completely DETERMINISTIC. Give it the initial state $\psi(r,0)$ and the rules of the game and it gives you exactly what the later states $\psi(r,t)$ will be.
    - So where’s the randomness?
  - 2. It’s LINEAR. That means that if you have two different wave patterns that solve the equation, so does any combination of them. (That’s called superposition)
    - That’s just like small water waves.
What if that’s it?

What if the SEQ were to work exactly all the time, like Newton’s laws were supposed to:

\[ \psi : \text{a quantum spin;} \quad A: \text{apparatus;} \quad C: \text{cat} \]

\[
\left( \frac{\psi_u + \psi_d}{2^{1/2}} \right) A_0 C_0 \rightarrow \left( \frac{\psi_u A_u + \psi_d A_d}{2^{1/2}} \right) C_0 \rightarrow \left( \frac{\psi_u A_u C_L + \psi_d A_d C_D}{2^{1/2}} \right)
\]

The final quantum state contains BOTH live cat \( C_L \) and dead cat \( C_D \) because the SEQ is LINEAR

the same as the water wave coming from two sources contains the parts from each source.

The result of the solution of the linear wave equation is that the cat is both alive and dead, in a superposition. This does not mean "in a coma" or "almost dead" but BOTH fully alive and purring or thoroughly dead and decomposing.
You’re also made of quantum parts.

\[
\begin{align*}
\left(\frac{\psi_u + \psi_d}{2^{1/2}}\right) A_0 C_0 Y_0 &\rightarrow \left(\frac{\psi_u A_u + \psi_d A_d}{2^{1/2}}\right) C_0 Y_0 \\
\rightarrow \left(\frac{\psi_u A_u C_L + \psi_d A_d C_D}{2^{1/2}}\right) Y_0 &\rightarrow \left(\frac{\psi_u A_u C_L Y_{SL} + \psi_d A_d C_D Y_{SD}}{2^{1/2}}\right)
\end{align*}
\]

The solution of the linear wave equation now describes a superposition of a you who has seen the dead cat and a you who has seen the live cat!

If the linear wave equation describes the world of our experience, with no live-dead cats - it must describe many such worlds! With many different yous! Which of youse guys is for real?
Bad Ideas for “Measurement” Problem

1. "Hidden variables" were always around to determine the outcome of the experiments, so $\psi$ doesn't have to collapse. We saw these variables can’t be hidden anywhere in spacetime! (Einstein, DeBroglie, Bohm)

2. (folk version) Somehow $\psi$ collapses to one outcome, but don't ask how.

3. (formal Copenhagen) $\psi$ wasn't ever real, so don't worry about how it collapses. It was just a calculating tool.

4. "macro-realism"- $\psi$ does too collapse, but that involves deviations from the linear wave equation. (Pearle, …)

5. mentalism: $\psi$ does too collapse, due to "consciousness", which lies outside the realm of physics. (Wigner, …)

6. (Many Worlds). There's nothing but the linear equation, you just have to understand what it implies. " $\psi$ doesn't collapse, all those different branches occur but have no reason (until you understand the wave equation) to be aware of each other’s existence. (Everett, deWitt, Hawking …)