# Does God play dice - and when?

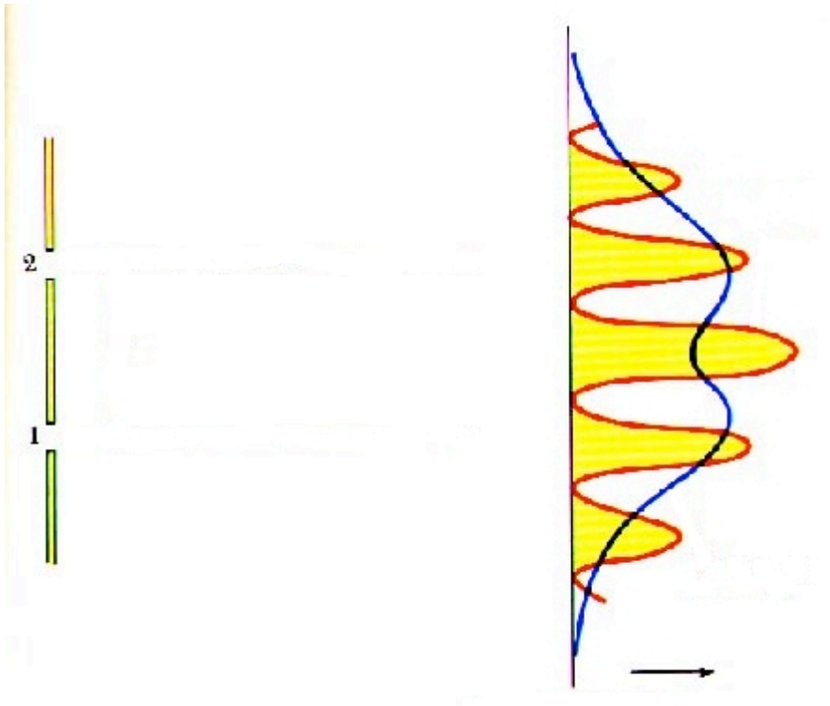
A short intro to the “measurement problem” in Quantum Mechanics

# The problem (sort of)

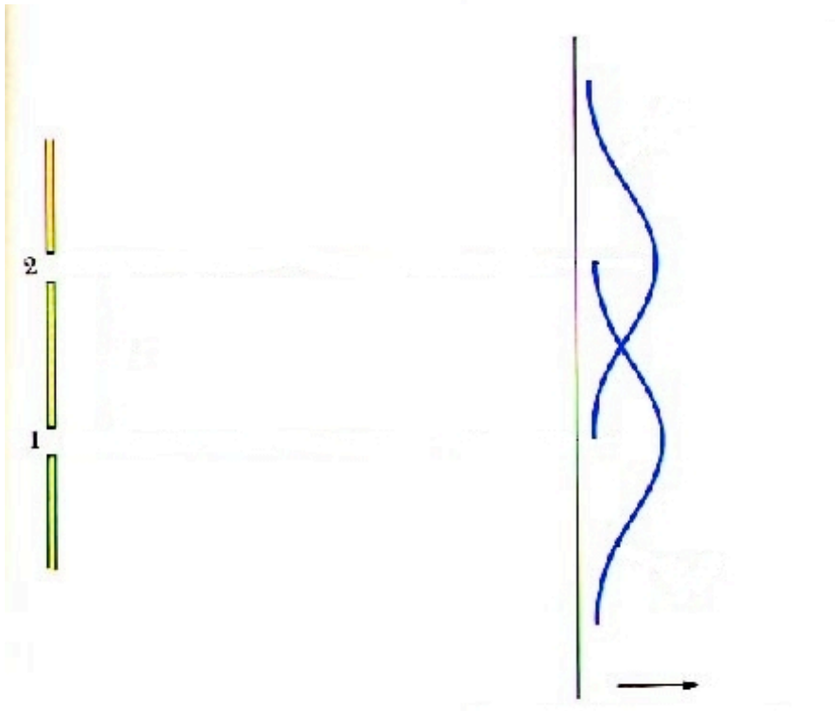
- Quantum systems can be in *superpositions*, seem to have several values for an observable at once
- If we try to measure, systems must decide, "collapses" into corresponding basis state
- But when does the measurement happen, what determines whether system has been measured or not?

# This way or that

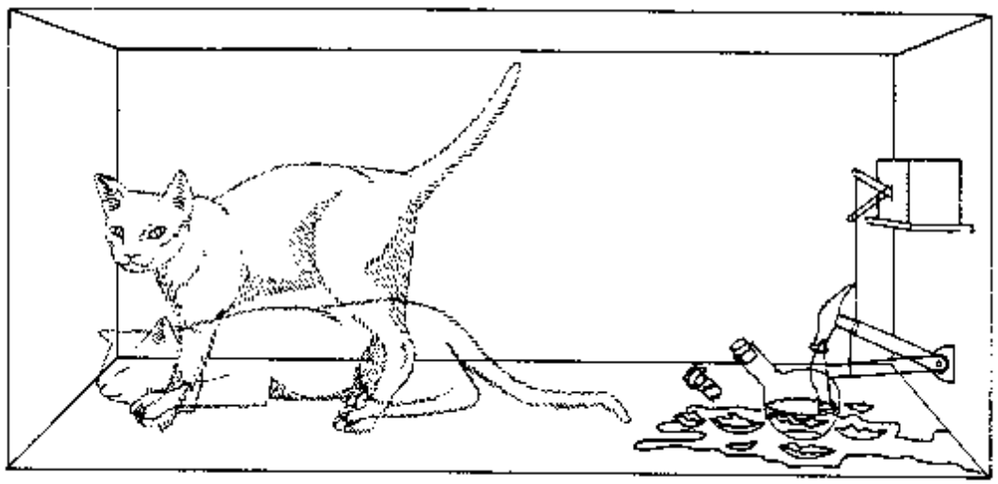
- Send electrons through double slit, get interference pattern, not additive pattern
- Act like waves, cannot go through just one slit or other to get interference

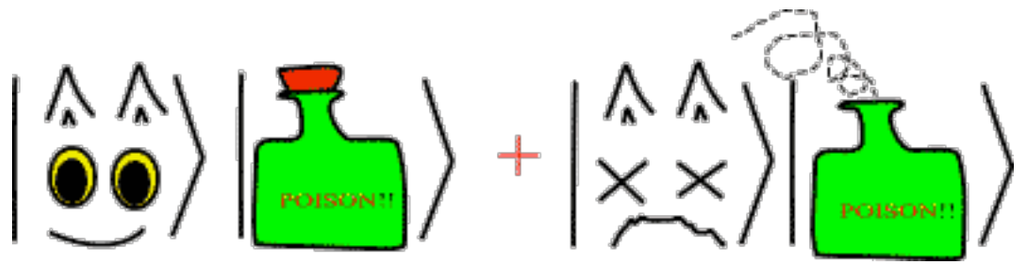



- Measure which slit; interference pattern disappears!
- Get additive pattern, each electron "decides" and goes through just one of the slits
- Weird, but electrons are small...



# To meow or not to meow





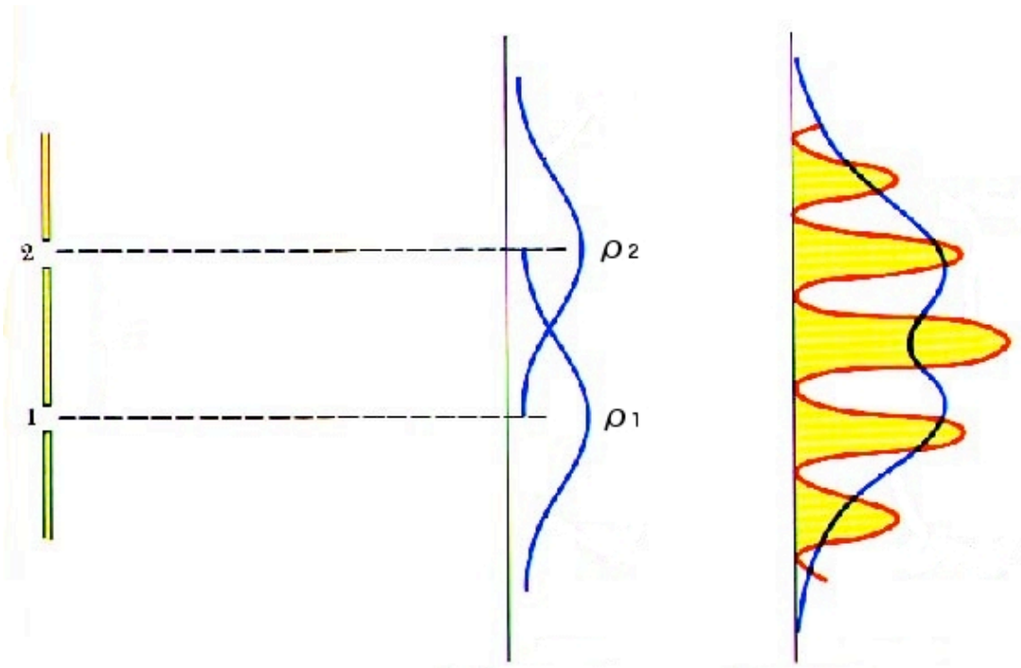

- E. Schrödinger 1935: cat in a box with radioactive element and flask of HCN
- Geiger counter linked to hammer, breaks flask if atom decays
- Evolves into superposition, cat does not live or die until measured!
- When is the cat measured? When box is opened? Does it measure itself?

# Down to size

- At some point superpositions break down, give us "sharp" classical world. Several proposals for how:
  - ✳ Conscious observers are special (seriously?)
  - ✳ Maybe QM breaks down at some size scale (but what scale, and what is meant by "size"?)
  - ✳ Maybe universe branches into parallel universes at each measurement, we live in one particular branch (ok, but how do we ever know?)

Whoa, so what was the problem again?

# Double slit revisited




- Distribution $\rho_1$ when slit 1 is open, $\rho_2$ when slit 2 is open

- Classically we expect $\rho_1+\rho_2$ when both slits are open, by addition of probabilities. *Does not agree with reality!*

But why do we expect addition of probabilities?

# Probability axioms

Classical probability theory can be constructed from the following axioms:

1. $P(A) \geq 0$ for all events $A$
2. $P(A \text{ and } B) = P(A|B)P(B)$
3. $P(A \text{ or } B) = P(A) + P(B)$ for mutually exclusive events $A$ and $B$
4. $P(A) = 1$ if $A$ occurs with certainty

But *why*?

# The Dutch Book argument

It's all about money...

- A bookie lets you bet arbitrary amounts of money on a set of events and all possible combinations
- Bookie assigns a "probability" $p$ (any number he wishes) to every event and combination of events
- If an event (or combination) does not occur, you lose the money you bet on it. If it does occur, bookie pays you $1/p$ times your bet

# The Dutch Book argument

- If probabilities are assigned in a way which violates the usual probability axioms, you can find a combination of bets such that the bookie runs a net loss *every single time, regardless of what events occur!*

- If probabilities are a measure of belief/risk, then probability axioms are rules which all agents *must* follow to avoid guaranteed loss

- But, this assumes that you can bet on *any* combination of events, and crucially that you can *verify* whether any event occurred or not

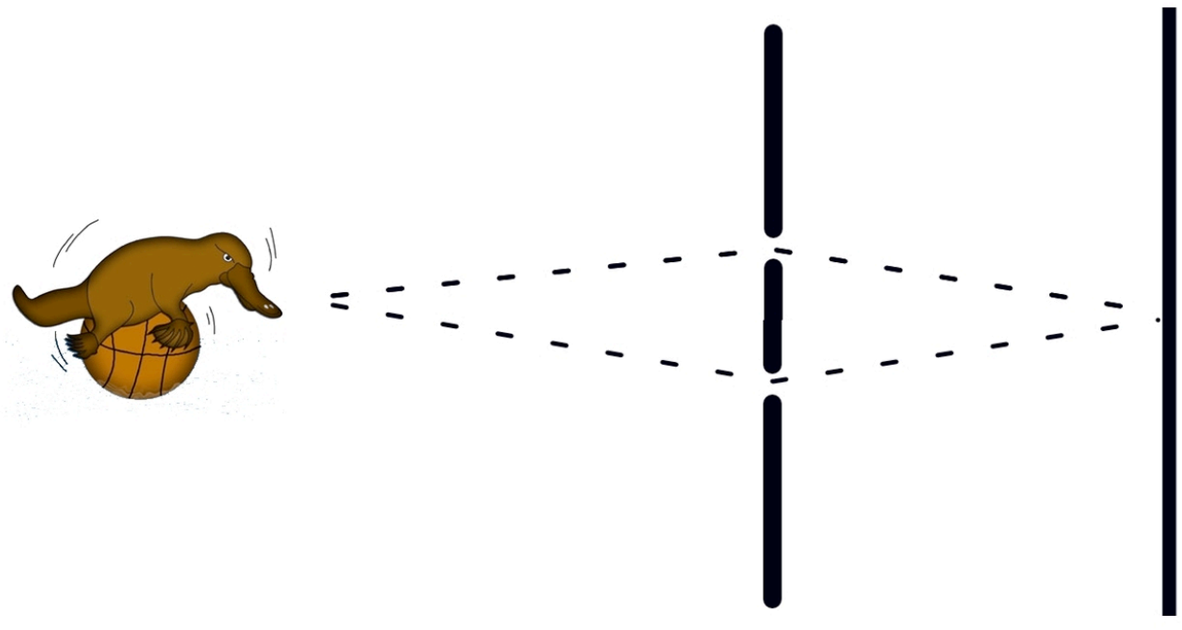
# “Dutch” and double slit

- Interference pattern emerges only if it is impossible *even in principle* to infer which slit the particle went through
- There must not exist any which-way information anywhere in the universe. Cannot check whether particle went through slit 1 or 2. *Are not events*, Dutch Book does not apply, no addition of probabilities
- If we *can* infer, in principle, which way the particle went, then Dutch book does apply. Particle must obey classical probability theory, and we get additive pattern, no interference. Has effectively *been measured*

# Measurements, dice and determinism

- So, an observable is measured when the environment records information about its value
- Key is interactions with the environment, *no need for conscious observers*
- But when does environment collapse? Just pushing the problem outwards here. Does environment require conscious observers to collapse?
- And what about conscious observers themselves? Can they be in superposition states? Don't they measure themselves?

# Information vs. observers



What if we send a conscious observer through a double slit

- Does the observer know which slit he/she went through? If so, must see slit, i.e. absorb photons. *This leaves a record in the environment*

- Alternatively, observer absorbs no photons, but then does not know which slit he/she went through! No which-way information, not even in brain of observer, hence there can be an interference pattern

# Not just disorientation

- Issue is not just that the observer does not know where he/she is
- As long as there *does not exist* any information about path of observer, we can obtain results inconsistent with assuming that the observer went along a definite path at all!
- Point is what information is in principle available, not whether any conscious observer observes it or not

# Of cats and curiosity

But what of Schrödinger's poor kitty? It lives or dies depending on which "path" it takes, so it *has* to know!

- Cat knows what happens to it and the inside of the box, so it does *not* describe itself with a superposition state
- If no information leaks out, we *cannot* know even in principle, so we *do* describe the cat and nucleus as being in a superposition state!
- No contradiction here; Cat sees itself living or dying with 50% probability, we see the same thing if we open the box

# Of cats and curiosity

No problem as long as we think of quantum states as being statistical functions *assigned to systems by observers*, and *depending on what information is in principle accessible to an observer*!

But wait a minute...

...cat says it's dead or alive with 50% probability...

...we say it's in an equal superposition state.

Surely those aren't equivalent statements!?

# A cat with nine unitary lives

Sure aint...

- Superposition state has the form $|\mathrm{alive}\rangle + e^{i\theta} |\mathrm{dead}\rangle$
- Knowing phase θ we can apply a unitary transformation, use interference to e.g. make cat dead or alive with certainty! (sort of a "Catamard" gate)
    - But no record must allow us to infer whether cat was dead or alive along the way. *Cat's memories must be wiped*
    - In the end, cat's and our state assignment agree, and neither knows that they ever differed!

Fine fine! But how can physical quantities have several values at once, or no definite value at all? How can a cat be dead and forget?

# “The Matrix” strikes again

How to understand what it means that position, momentum, etc. is not “defined”, without abandoning Common Sense and Sanity™?

- Think of a computer program trying to explore the computer it is running on (that’d be us)
- Can discover stuff only by calling functions, provided by the OS:

```
float FindElectronPosition();
float FindElectronMomentum();
```

- Gets a value whenever it calls a function. But what value does a function “have” when the program is *not calling* it? Does this question even make sense?

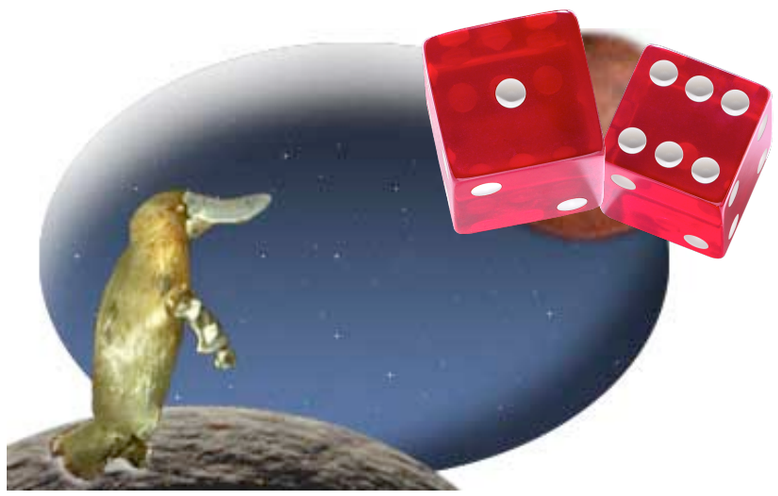
# “The Matrix” strikes again

- *Can* make sense e.g. if the function looks like this:

```
float FindElectronPosition()
{
    global float electronPosition;
    return electronPosition;
}
```

- But doesn’t have to be this way, function can return complicated dynamically generated value, and change the memory of the computer along the way
- The world view of the program is limited by the structure of the system it is running on!

# Conclusions (of a sort)



- We are physical beings, what we can learn about the physical universe and physical laws is governed and limited by how those physical laws allow us to interact with it
- Quantum Mechanics is (at least) a statistical description of the universe which takes such limitations into account
- *No paradoxes*, as long as we think in terms of what information is in principle accessible to observers, and don't dabble in defining things independently of our interactions with the physical universe