http://www.physics.utoronto.ca/~aephraim/201/finalpaper.html

The paper should be "long enough to cover the subject yet short enough to hold the interest" -- for instance, between 12 and 16 double-spaced pages (about 3500 words), not including the bibliography or any figures you choose to include.
It should critically examine a scientific topic which builds on material we have discussed in class, but going either further or deeper than we have during the course. It is expected that you will consult a range of published sources, and use proper footnotes (or endnotes) and a complete bibliography. The paper should demonstrate your ability to analyze conceptual questions about the science critically, making logical arguments and distinguishing areas where reasonable people could differ from those where the answer is more or less clear-cut.

The paper will be due on the last day of class (Tuesday, December 4th), but will only be accepted if you have first
(a) submitted a proposed title to your TA by approval (due 3 November); and
(b) **submitted a partial bibliography and/or rough outline to your TA for approval (due 17 November)**.

The title & outline/bibliography will not be graded, but will give your TA an opportunity to provide feedback lest you pursue a topic which doesn't really fit the parameters of the assignment (which could prevent you from getting a good grade on the paper itself).

Some possible titles might include:

- The evolution of ideas of locality in classical and modern physics
- The uses of entanglement for quantum information processing
- Thermodynamic and cosmological arrows of time
- The "clockwork universe": arguments over determinism in classical and modern physics

[...]

- The discovery of dark matter, and what we currently know about it
- The origin of order in a world where entropy increases
- Feynman diagrams and antimatter as electrons travelling backwards in time
- Possibilities for time machines following the laws of physics (as we currently understand them)

Feel free to consult me and/or the TA's for advice about these or any other topics, and/or for help in tracking down some initial sources if necessary.

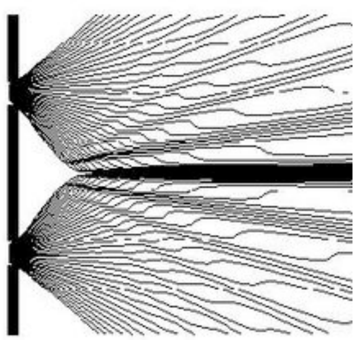
Some well-known features of QM

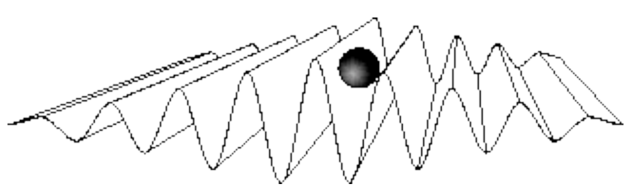
- Wave-particle duality (“complementarity”)
- Uncertainty principle (Heisenberg)
- Randomness (lack of determinism)?
- The world is discrete, not continuous?
- Quantum jumps ?
- Measurement affects reality?
- Nonlocality? All things “entangled”?

The "orthodox" ("Copenhagen") viewpoint, more or less...

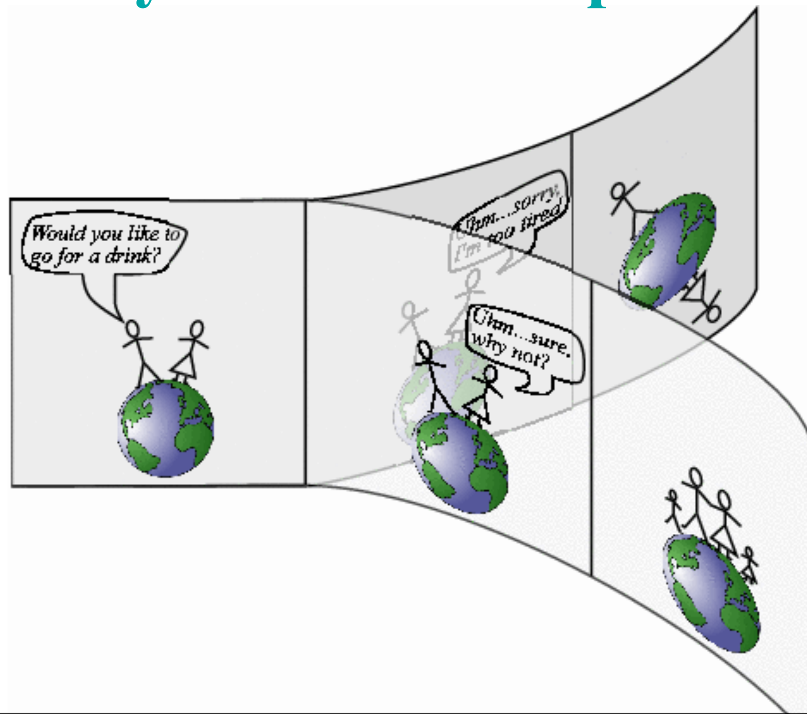
1. A system is completely described by a wave function ψ, representing the state of the system.
2. The description of nature is essentially probabilistic, with the probability of an event related to the square of the amplitude of the wave function related to it. (The Born rule, after Max Born)
3. It is not possible to know the value of all the properties of the system at the same time; those properties that are not known with precision must be described by probabilities. (Heisenberg's uncertainty principle)
4. Matter exhibits a wave–particle duality. An experiment can show the particle-like properties of matter, or the wave-like properties; in some experiments both of these complementary viewpoints must be invoked to explain the results, according to the complementarity principle of Niels Bohr.
5. Measuring devices are essentially classical devices, and measure only classical properties such as position and momentum.
6. The quantum mechanical description of large systems will closely approximate the classical description. (The correspondence principle of Bohr and Heisenberg.)

An alternative: de Broglie/Bohm "pilot waves"





Yet another picture: Many-Worlds Interpretation



Many-minds?

No one knows what this "branching of universes" would really mean, and why each of us only experiences just one.

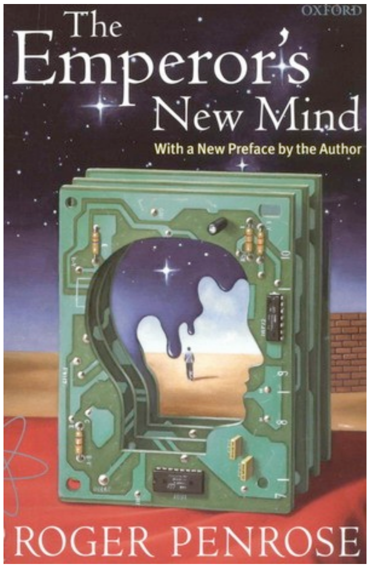
The real content of the interpretation is this:

we know Schrödinger's equation is right. We have no evidence that we need anything *else* (like "collapse), except for one fact: you and I feel like one thing or another (never a "superposition" like Schrödinger's cat) happens.

So what remains to be explained?

Consciousness. (About which physics can't say anything right now anyway!)

Roger Penrose



Physics has solved almost everything.

There are three things we don't understand:

- **quantum "collapse"**
- **quantum gravity**
- **consciousness**

Since we're so smart, it's more likely that there's only *one* thing we don't understand, and it explains all of these.

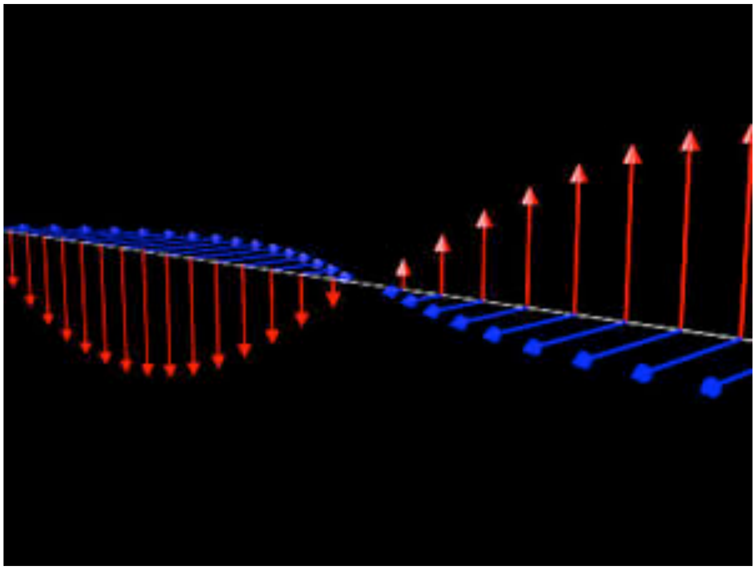
Wigner, Wheeler, et al.: maybe collapse really just occurs when conscious beings observe things?
Penrose: When things get too big & heavy (gravity), quantum states collapse (for a reason we don't yet know). And the brain is also quantum, of course, so probably consciousness arises at the same time

Why should we believe any of these? Where does this "probability" come from?

- Wave-particle duality in interference
- Other measurements -- e.g. polarized photons, or the spin of electrons/atoms ("Stern-Gerlach effect)...

Polarized light...

Remember: light (classically, at least) is made up of electric and magnetic fields, which *point in particular directions* (since they represent forces you could experience)... turns out light of a given colour comes in different forms based on these directions...



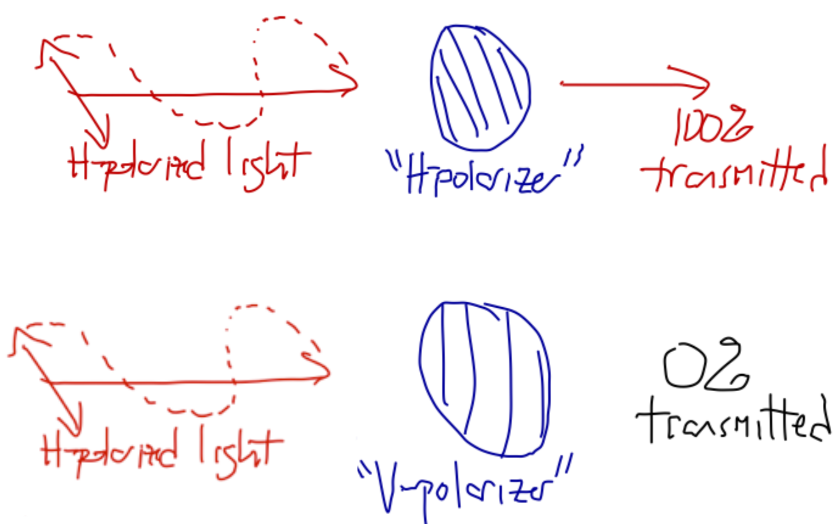
For more on polarisation:

http://www.upscale.utoronto.ca/PVB/Harrison/SternGerlach/Polarisation.html

http://www.exo.net/~pauld/summer_institute/summer_day8polarization/day8_polarization.html

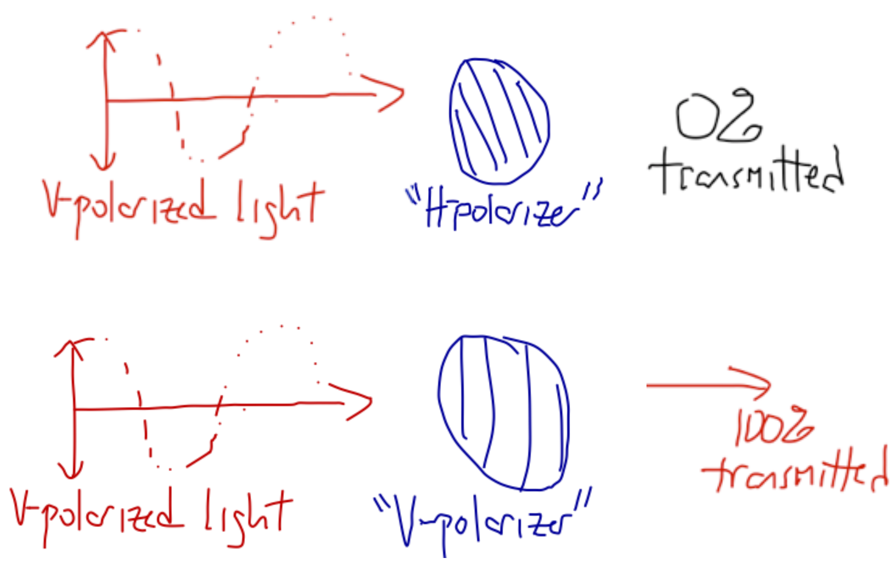
Measuring polarizations

pol   Page 1 of 1 - Nov 24, 2011

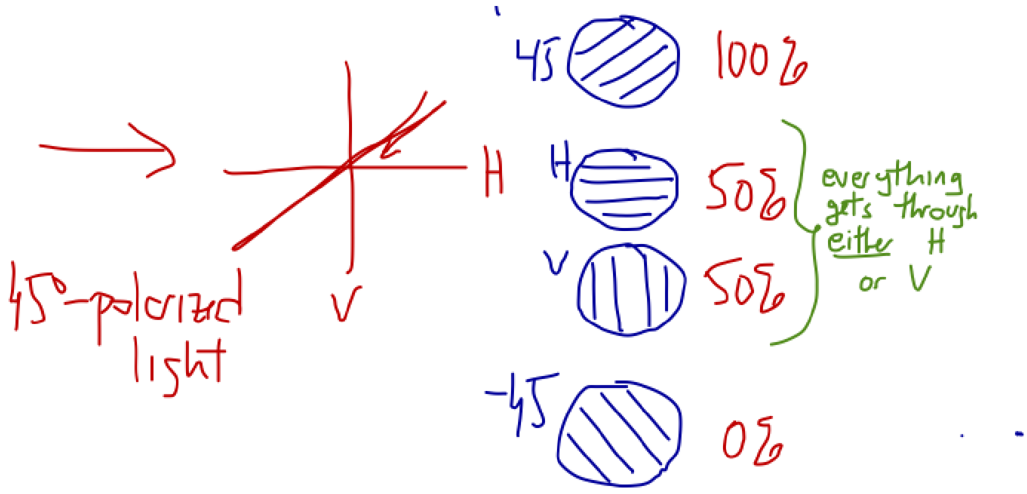


Measuring polarizations

pol   Page 1 of 1 - Nov 24, 2011



Measuring polarizations



What of single photons?

- There's no such thing as "50% of a photon"
- It must be that 50% *of the photons* get through, and 50% don't.
- (Did each photon know whether it would get through or not, or does it choose randomly?)
- We can "sort" photons by

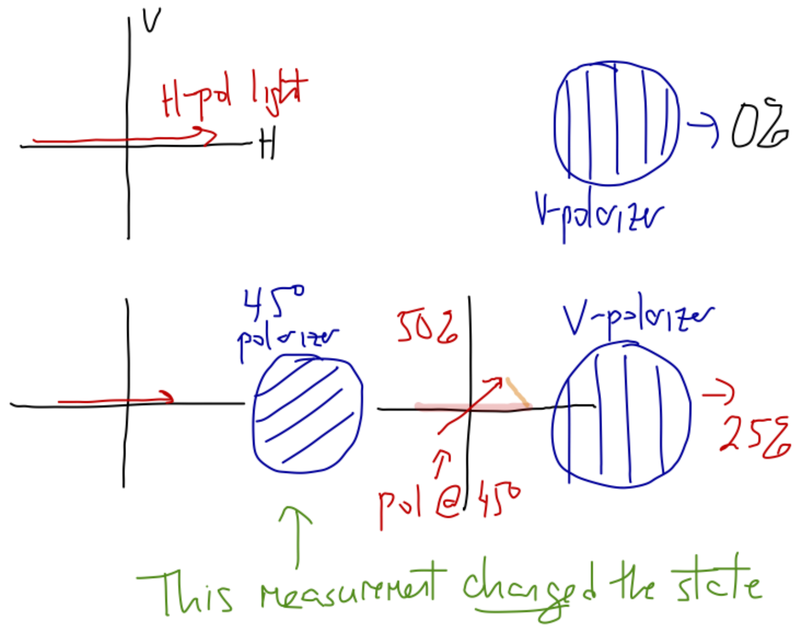
{which get through H / which get through V} or

{which get through 45 /which get through –45}.

So does each photon "know" its "H/V" polarization *and* its "±45" polarization? Or is our description complete, and the photons really have to flip coins to decide what to do?

THIS IS ANOTHER KIND OF "UNCERTAINTY PRINCIPLE"

What if we measure *both*?



Conclusion?

- Either the particle doesn't actually *"know"* its "HV polarisation" and its "±45 polarisation, or
- if it *does* know both, then measuring one changes the other.

(It knew it didn't want to go through the V polarizer, but after I measured 45, it could have changed its mind...)

Ensemble interpretation

- The attempt to conceive the quantum-theoretical description as the complete description of the individual systems leads to unnatural theoretical interpretations, which become immediately unnecessary if one accepts the interpretation that the description refers to ensembles of systems and not to individual systems.

  --Albert Einstein

But then *either* we wait for a more complete theory...
or if QM is all there is, does that mean we accept that physics simply *can't talk about* individual events??

Mermin: "Ithaca Interpretation"

II. Six Desiderata for an Interpretation of Quantum Mechanics.

- (1) Is unambiguous about objective reality.
- (2) Uses no prior concept of measurement.
- (3) Applies to individual systems.
- (4) Applies to (small) isolated systems.
- (5) Satisfies generalized Einstein-locality.
- (6) Rests on prior concept of objective probability.

IV. The Ithaca Interpretation of Quantum Mechanics

Having only begun looking at quantum mechanics from the point of view of my six Desiderata and two Theorems, I have only scattered, incomplete conclusions to report. At this stage the Ithaca Interpretation is rather fragmentary. Central to it is the doctrine that *the only proper subjects of physics are correlations among different parts of the physical world.* Correlations are fundamental, irreducible, and objective. They constitute the full content of physical reality. There is no absolute state of being; there are only correlations between subsystems.

Once it occurs to you to put it this way it sounds like a trivial point. For how could it be otherwise? One might imagine a God existing outside of the World with direct unfathomable Access to its Genuine Essence. But physics is more modest in its scope than theology. It aims to understand the world in the world's own terms, and therefore aims only to relate some parts of the world to others. For physicists, if not for theologians, this reduction in scope ought not to be a serious limitation.

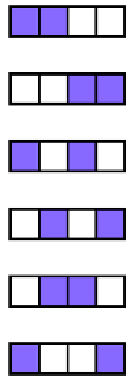
"Epistemic" (vs. "ontic") models

"The quantum state is a state of knowledge, not a state of reality"

But is more knowledge *conceivable*, or are we only *allowed* to have partial knowledge?

Spekkens "toy model": "If one has maximal knowledge, then for every system, at every time, the amount of knowledge one possesses about the ontic state of the system at that time must equal the amount of knowledge one lacks."

Maybe these are the only states I can distinguish...



?

The quantum state cannot be interpreted statistically

Matthew F. Pusey, Jonathan Barrett, Terry Rudolph

(Submitted on 14 Nov 2011)

Quantum states are the key mathematical objects in quantum theory. It is therefore surprising that physicists have been unable to agree on what a quantum state represents. There are at least two opposing schools of thought, each almost as old as quantum theory itself. One is that a pure state is a physical property of system, much like position and momentum in classical mechanics. Another is that even a pure state has only a statistical significance, akin to a probability distribution in statistical mechanics. Here we show that, given only very mild assumptions, the statistical interpretation of the quantum state is inconsistent with the predictions of quantum theory. This result holds even in the presence of small amounts of experimental noise, and is therefore amenable to experimental test using present or near-future technology. If the predictions of quantum theory are confirmed, such a test would show that distinct quantum states must correspond to physically distinct states of reality.

Hidden variables? The EPR “paradox”

Q: what do we need to do, to decide whether or not particles “really have” positions, independent of the fact that the quantum state doesn’t describe one position?

- **“If, without in any way disturbing a system, we can predict with certainty the value of a physical quantity, then there exists an element of reality corresponding to that quantity.”**

- **If two systems are separated by a distance d, nothing I do to one of them can affect the other in a time < d/c.**

If by measuring system 1, I can figure out what system 2’s position is *at that instant*, I am learning about system 2 without disturbing it...

Einstein, Podolsky, & Rosen (1935)

Source

Alice **Bob**

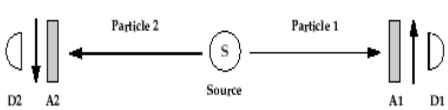


FIG. 1. Bohm’s version of the EPR Gedankenexperiment

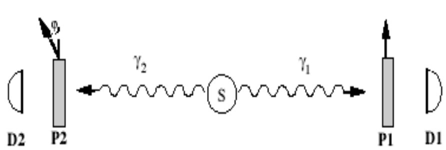


FIG. 2. Optical version of EPR experiment

2 particles emitted together at the same time with opposite speeds.

If Alice measures her particle's position, she knows Bob's. But if she measures her particle's momentum, she knows Bob's.

Did her measurement "affect" Bob's particle instantaneously?
Spooky action at a distance
Or did Bob's particle already have both?
Hidden variables (QM "incomplete")