Lecture 1, Tues Jan 17: Course Intro, Church-Turing Thesis

- Quantum Information Science is an inherently interdisciplinary field (Physics, CS, Math, Engineering, Philosophy)
- It's about clarifying the workings of quantum mechanics.
  - We use it to ask questions about what you can and can't do with quantum mechanics
  - It can help us better understand the nature of quantum mechanics itself.
- Professor Aaronson is very much on the theoretical end of research.
  - Theorists inform what experimentalists make, which in turn informs theorists' queries

Today we'll articulate several "self-evident" statements about the physical world. We'll then see that quantum mechanics leaves some of these statements in place, but overturns others--with the distinctions between the statements it upholds and the ones it overturns often extremely subtle! To start with…

Probability ($P \in [0,1]$) is the standard way of representing uncertainty in the world.
Probabilities have to follow certain obvious axioms like:

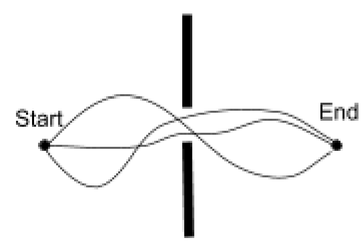
$P_1 + \cdots + P_n = 1$ mutually exclusive exhaustive possibilities sum to 1

$P_i \geq 0$

As an aside:

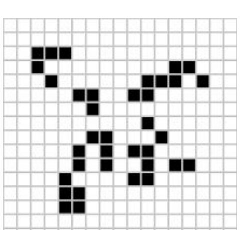
> There's a view that "probabilities are all in our heads." Which is to say that if we knew everything about the universe (let's say position/velocity of all atoms in the solar system) that we could just crunch the equations and see that things either happen or they don't.

Let's say we have two points separated by a barrier with an open slit, and we want to measure the probability that a particle goes from one point to the other. It seems obviously true that increasing the number of paths (say, by opening another slit) should increase the likelihood that it will reach the other end.



We refer to this property by saying that probabilities are ***monotone***.

Locality is the idea that things can only propagate through the structure of the universe at a certain speed.



When we update the state of a little patch of space, it should only require knowledge of a little neighborhood around it. Conway's Game Of Life (left) is an apt comparison: things you do to the system *can* affect it, but they propagate only at a certain speed.

Einstein's Theory of Relativity explains that a bunch of known physics things are a direct result of light's finite speed. Anything traveling past the speed of light would be tantamount to travelling back in time.

Local Realism says that any instantaneous update in knowledge about far away events can be explained by correlation of random variables.

For example, if you read your newspaper in Austin, you can instantly collapse the probability of your friend-in-San-Francisco's newspaper's headline to whatever *your* headline is.

Some popular science articles might talk about how you measure the spin of one particle, and then instantaneously you know the spin of another particle on the other side of the galaxy. But *unless and until* something more is said about it, that's no different from the case of the newspapers, and seems 100% compatible with local realism!

The **Church-Turing Thesis** says that every physical process can be simulated by a Turing machine to any desired precision.

The way that Church and Turing understood this was as a definition of computation, but we can think of it instead as a falsifiable claim about the physical world. You can think about this as the idea that the entire universe is a video game: you've got all sorts of complicated things like quarks and whatnot, but at the end of the day, you've got to be able to simulate it on a computer.

Theoretical computer science courses can be seen as basically math courses. So what *does* connect them to reality? The Church-Turing Thesis.

The **Extended Church-Turing Thesis** says moreover that, when we simulate reality on a digital computer, there's at most a polynomial (e.g., linear or quadratic) blowup in time, space, and other computational resources.

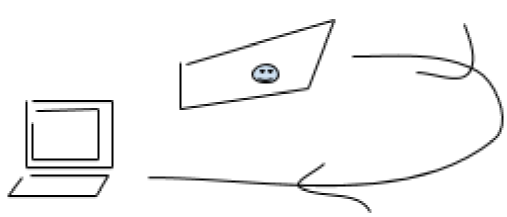
So, what does quantum mechanics have to say about each of these principles?

To give you a teaser for much of the rest of the course:

We'll still use probabilities. But the way we'll *calculate* probabilities will be totally different, and will violate the axiom of monotonicity. That is, *increasing* the number of ways for an event to happen, can *decrease* the probability that it happens.

Locality will be upheld. But *Local Realism* will be overthrown. And if those two principles sounded like restatements of each other---well, quantum mechanics will dramatically illustrate the difference between them!

As we'll see, the Church-Turing Thesis still seems to be in good shape, even in light of quantum mechanics.



Using time dilation, you could travel billions of years in the future and get results to hard problems. Fun! But you'd need a *LOT* of energy, and if you have that much energy in one place you basically become a black hole. Not so fun!

But the *Extended* Church-Turing Thesis seems to be false, with quantum computing standing as a glaring counterexample to it--possibly the *one* counterexample that our laws of physics allow.

With that said, however, one can formulate a quantum version of the Extended Church-Turing Thesis, which remains true as far as anyone knows today.