Quantum Foundations Lecture 1

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HSC112

Emlyn Hughes on Quantum Theory

- In 2013, Prof. Emlyn Hughes at Columbia University introduced his GenEd class on quantum theory in the following way.
- Warning: This video contains offensive imagery

  https://www.liveleak.com/view?i=1cc_1361276541
- How does this video make you feel about quantum mechanics?

Emlyn Hughes on Quantum Theory

"In order to learn quantum mechanics, you have to strip to your raw, erase all the garbage from your brain, and start over again. Nothing you have learned in your life up till now is in any way helpful to prepare you for this, because everything you do in your everyday life is totally opposite to what you are going to learn in quantum mechanics. And so, I've been tasked with the impossible challenge of having to teach you quantum mechanics in one hour. What, basically the most brilliant minds, Einstein and so on, couldn't figure out working on it their whole life."

The not-so subtle subtext

"You are going to be very confused by quantum mechanics. As much as if your physics professor did a weird performance art piece for no apparent reason. The smartest people in the world do not understand it. Therefore, I, an extremely smart professor, cannot possibly be expected to teach you, with your small undergraduate brains, this subject in a way that you can understand it. Nevertheless, suck it up because you have to pass an exam on it at the end"

My interpretation of what Emlyn Hughes meant.

An Obligatory Feynman Quotes

"I think I can safely say that nobody understands quantum mechanics" – "The Character of Physical Law", chapter 6, p. 129

- This quote appears in almost every popular science book about quantum theory, and many textbooks too.
- I think it is an excuse for teaching quantum theory badly, i.e. "I am confused about quantum theory. The smartest physicist was confused too. Therefore, you will be confused and it is not my fault."

A lesser known Feynman quote

"We always have had … a great deal of difficulty in understanding the world view that quantum mechanics represents. At least I do, because I'm an old enough man that I haven't got to the point that this stuff is obvious to me. Okay, I still get nervous with it. And therefore, some of the younger students … you know how it always is, every new idea, it takes a generation or two until it becomes obvious that there's no real problem. It has not yet become obvious to me that there's no real problem. **I cannot define the real problem, therefore I suspect there's no real problem, but I'm not sure there's no real problem.**" - "Simulating Physics with Computers", *International Journal of Theoretical Physics*, volume 21, 1982, p. 467-488

- Our task is to approach this as a scientific question. Specifically:
  - Define the theory in as clear and general a way as possible.
  - Define the real problem.
  - Show how we can use math, physics, philosophy and experiment to address the problem.
  - Explore the proposed solutions.

Course Outline

1. Introduction (today)
2. Mathematical Background (week 1)
   - Linear and convex spaces
3. Generalized Probabilistic Theories (week 2)
   - What should a general theory of physics look like?
4. Postulates of Quantum Mechanics (week 3)
   - What does quantum theory look like?
5. Philosophy of Physics (week 3)
   - How can we define the problem?
6. Phenomenology of Quantum Mechanics (week 4)
   - Which experiments and effects are deemed problematic?
7. Tensor Spaces (week 5-7)
   - A cool way of doing linear algebra with diagrams
8. The Generalized Quantum Formalism (week 7-9)
   - Everything I taught you in PHYS451 and 452 is a lie!
9. Ontological Models and No-Go Theorems (week 10-12)
   - What must reality be like if quantum theory is true?
10. The Classical Limit of Quantum Theory (week 13)
    - If it is so weird, how come we don't see it every day?
11. Interpretations of Quantum Mechanics (week 14-15)
    - What possible consistent theories of reality are theore?

1) Introduction

i. Some Wrong Answers
ii. A (biased) History of Quantum Theory
iii. Operational Approaches to Physical Theories

1.i) Some Wrong Answers

- Quantum theory describes a world far from our everyday experience, so there is no reason it should be comprehensible. We have to get used to abstraction.
  - The same is true of relativity.
- Interpretation of quantum theory is irrelevant for practical applications, let's leave it to philosophers.
  - This is a selection effect.
  - Modern applications like quantum information/computation show that thinking about foundations is useful.
  - It leads to novel experiments, e.g. Bell's theorem
  - It may suggest how to adapt the theory beyond its current scope, e.g. in quantum gravity.

1.ii) A (biased) History of Quantum Theory

Old Quantum theory

$E = hf$

$p = h/\lambda$

etc.

Quantum Mechanics

Heisenberg matrix mechanics (1925)

Schrödinger wave mechanics (1926)

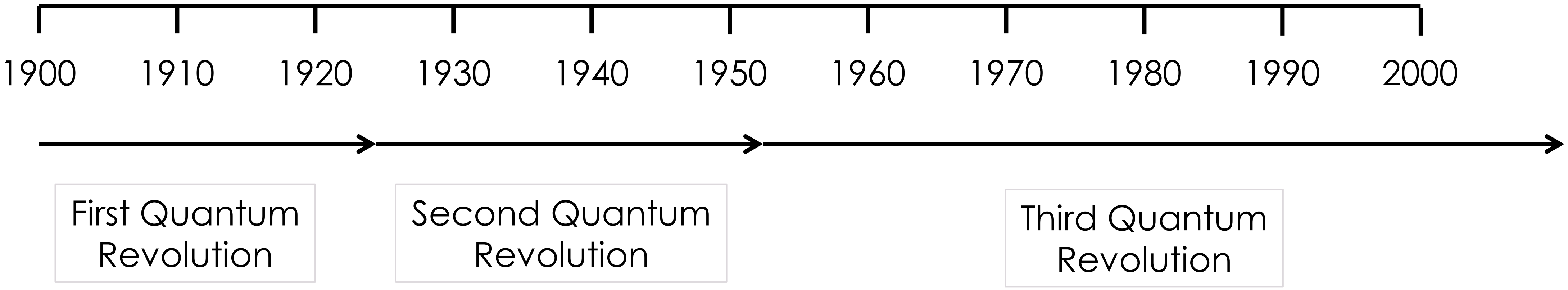
Hilbert space formalism (1930-32)

Taking Quantum Theory Seriously As A Fundamental Theory

Bohm (1952), Everett (1957), Bell (1964-)

Wavefunction of the universe

Quantum Computers



First Quantum Revolution

- Old quantum theory was not a full physical theory. Just a series of ad hoc rules that contradicted existing physics.
- It was necessary to judiciously choose which part of the system to apply quantum rules to, leaving the rest classical.
- This survived into Copenhagen-style quantum mechanics.
  - Physicists were not particularly bothered. They were used to doing it.
  - Copenhagen made this into a virtue rather than a vice.

Second Quantum Revolution

- Heisenberg’s matrix mechanics was originally based on the idea that systems were always in (what we now call) stationary states, and from time to time would jump between them indeterministically.
  - This was inspired by the Bohr atom.
- Heisenberg found that he needed physical quantities (observables) to be matrices to get this to work.
- Non-stationary states were a later addition (with Born and Jordan), and quite alien to Heisenberg’s initial thinking.

Second Quantum Revolution

- Schrödinger initially thought of his wavefunction as a physical field. There was no probability rule. Particles were supposed to emerge somehow from the dynamics.
- This was given up when it was found that, with realistic Hamiltonians, wavefunctions always spread in time.
- Entanglement also makes the physical field interpretation difficult.
- Max Born introduced the probability wave interpretation in 1926. Schrödinger was later forced to accept it.

Second Quantum Revolution

- The Heisenberg and Schrödinger theories were unified (by Schrödinger, Dirac, and von Neumann) resulting in the modern Hilbert space formalism.
  - Note that there were initially two perfectly coherent ideas of what quantum theory is about. The unification is true to neither of them.
  - Heisenberg had to "borrow" non-stationary states. Schrödinger had to "borrow" probabilities.
  - As a result, it became completely unclear what the theory was fundamentally about.

The Two Churches of Quantum Theory

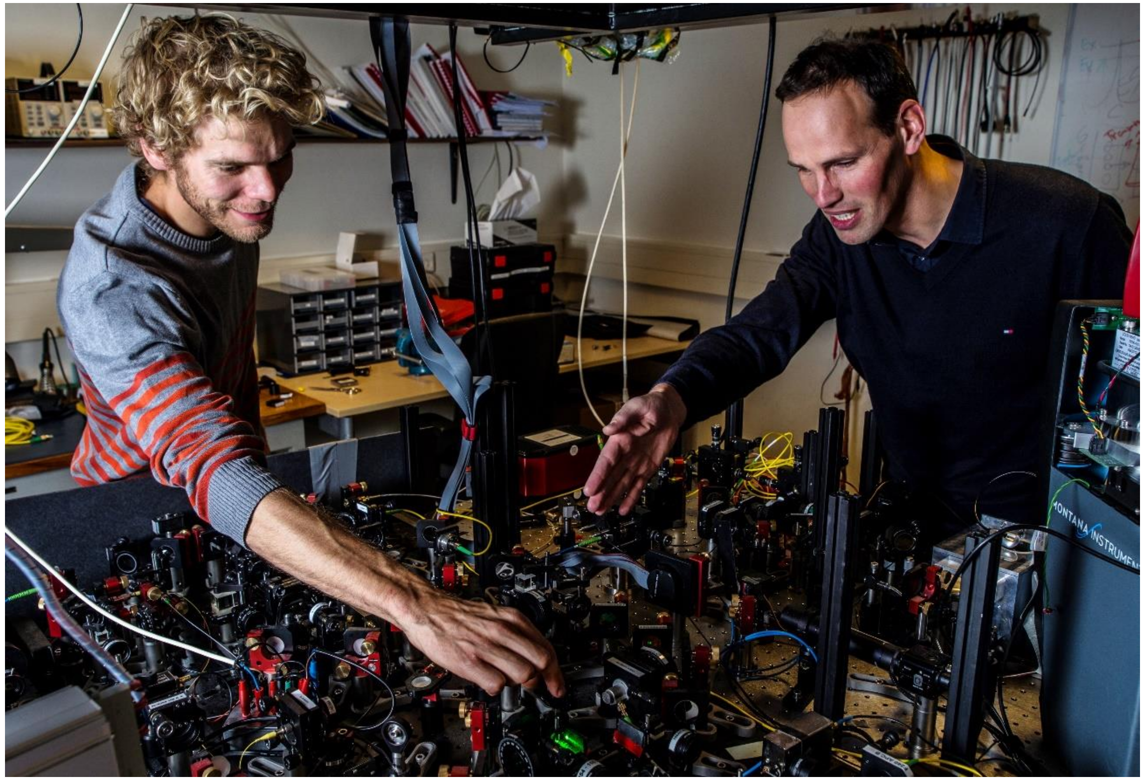
- Schrödinger and Heisenberg are *mathematically* equivalent, but a conceptual divide still exists.
- The Church of the Larger Hilbert Space:
  - Quantum theory is a dynamical theory, much like a classical field theory, but with a weirder object called a wavefunction replacing the classical field. All is to be derived from a wavefunction evolving unitarily in time.
- The Church of the Smaller Hilbert Space
  - Something weird happened to the algebra of observables, they became non-commutative. Quantum theory is the only consistent probability theory for such observables.

Third Quantum Revolution

- Starting in the 1950’s, People like Bohm and Everett were dissatisfied with the Copenhagen idea that there was a necessary split between the classical and quantum worlds.
  - If quantum theory is fundamental, we should be able to describe the whole universe as a quantum system, with no external classical world.
- This led to a reanalysis of foundations, leading to things like Bell’s theorem and quantum information.
- This has been a very slow-burn revolution.

1.iii) Operational Approaches to Physical Theories

Physics experiments can be complicated. You have to know a lot of background theory to understand how they work.



Bas Hensen and Ronald Hanson with the equipment used for the first loophole free Bell experiment in 2015 - credit QuTech http://qutech.nl

1.iii) Operational Approaches to Physical Theories

- In an *operational approach* we abstract away all of these concrete details and just ask about the general rules that connect our actions to our observations.
- Examples:
  - In thermodynamics, we talk about heat engines and the rules for coverting heat into work and vice versa. Independent of how the heat engines work or what they are made of.
  - In special relativity we ask what spacetime must be like if two postulates hold:
    - Physical laws look the same in all inertial frames
    - The speed of light is constant in all inertial frames
  - This is independent of the specifics of physical laws, e.g. electromagnetism or gravity.
- Einstein called these *principle theories*.

1.iii) Operational Approaches to Physical Theories

- We will treat physical processes as a *black boxes*:

- This will allow us to formulate physical theories, and quantum theory in particular, carefully without making unwarranted claims about the nature of reality.
- Of course, we shall eventually want to open the black box and see what is inside.