Balancing Mathematical Formalism and Experimentation Discussions in Quantum Mechanics: Student Perspectives on Learning and Quantum Measurement

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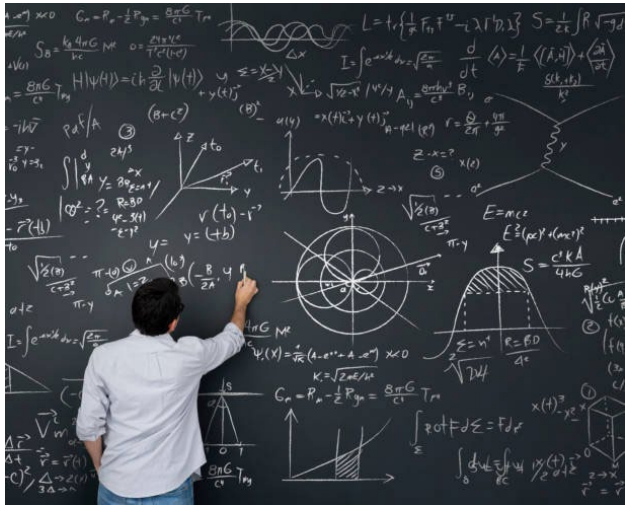
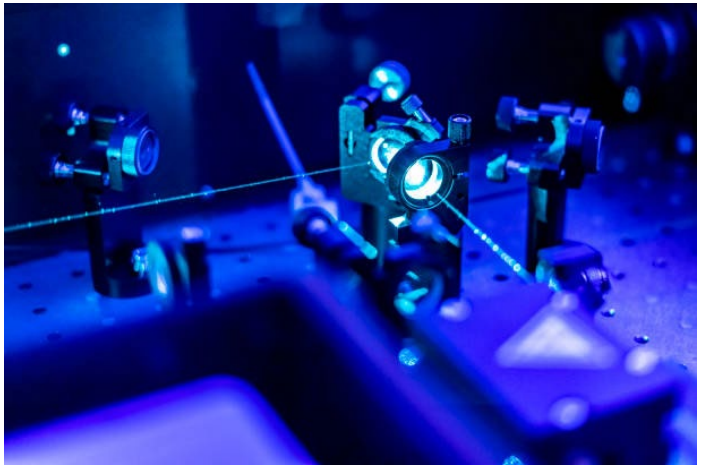
GEORGETOWN UNIVERSITY

How Should a Physics Instructor Spend Their Class Time?



Mathematical Framework



Experimental Understanding

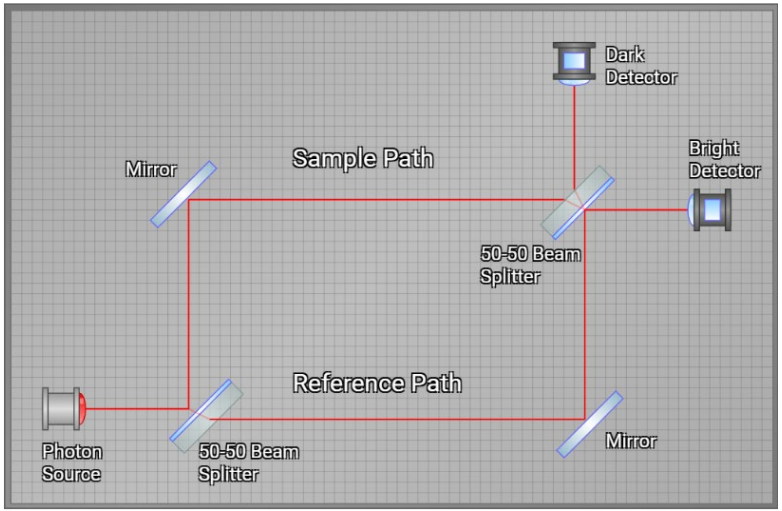
Difficulties with Experiments in Quantum Mechanics

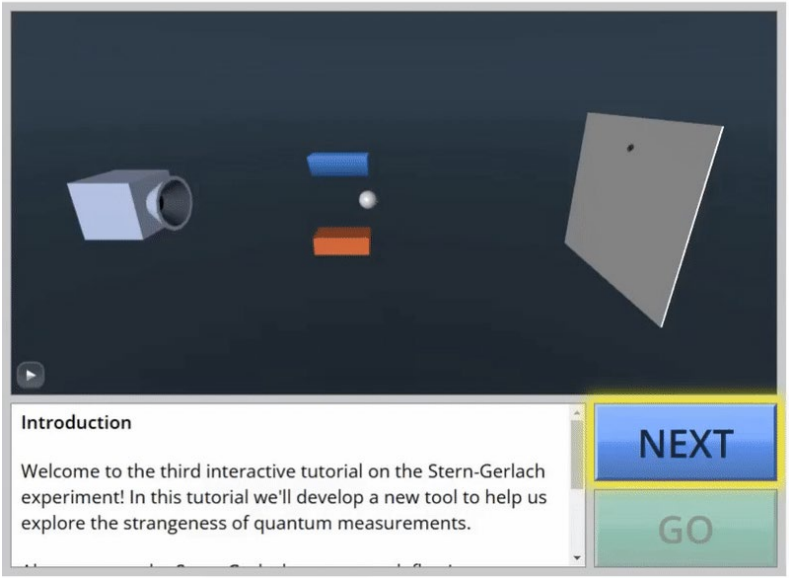
- Typically lecture -based with overloaded curriculum to teach quantum basics

- Difficulty in finding “true” quantum experiments that are:
  - Easily reproducible
  - Cheap
  - Engaging to students

Quantum Mechanics Course with Simulations

- Conceptually motivated “spins -first” approach with lecture material focused on learning about quantum experiments through tutorial -style simulations





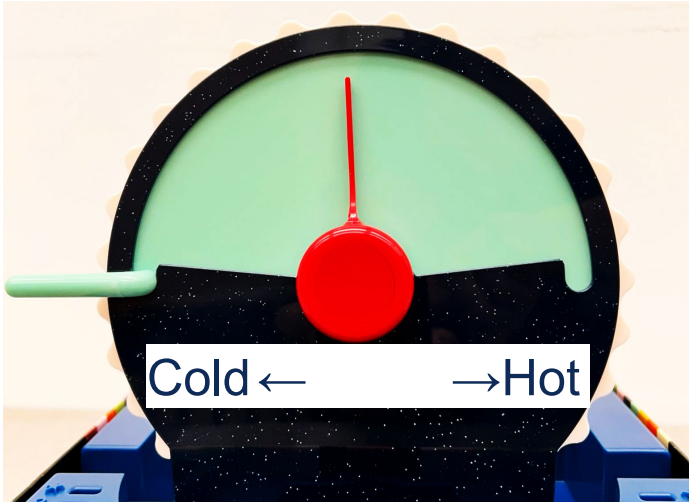
Interview Questions

- Interview 8 physics undergraduates at Georgetown
- Mixture of survey style questions with interview -style questioning

On a scale where 1 is the coldest possible in our solar system and 10 is the hottest possible in our solar system, how hot is a cup of coffee?

1	2	3	4	5	6	7	8	9	10

Cold Hot



Interview Structure

1. Benchmark Questions

2. Perceptions on Understanding Questions

3. Comparison Questions
   - Quantum vs. Intermediate

4. Perceptions on Course Pedagogy Questions

5. Comparison Questions
   - Mathematical vs. Experimental

Questions

1. Given the boundaries “Hate” and “Love,” where would the “Mathematical Formalism” or “Experimental Discussions” presented in the course fit on the Wavelength scale?

2. Given the boundaries “Completely Lost” and “Complete Understanding,” where would the “Mathematical Formalism” or “Experimental Discussions” presented in the course fit on the Wavelength scale?

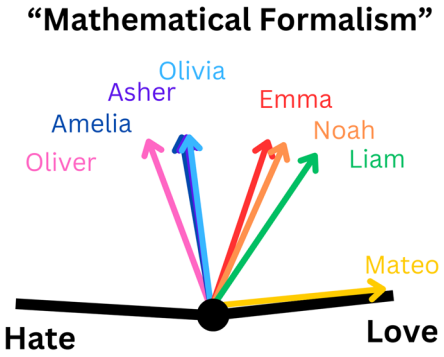
3. Given the boundaries “Mathematical” and “Experimental,” where would “Quantum Measurement” fit on the Wavelength scale?

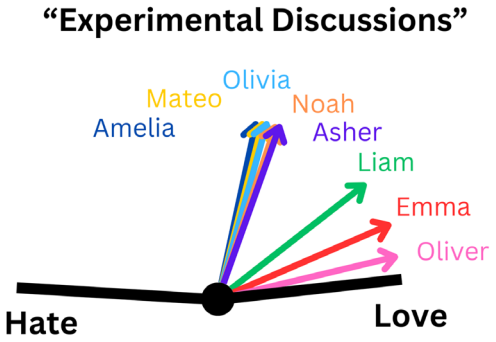
4. How would you relate the idea of “Quantum Measurement” with the Mathematical Formalism or Experimental Discussions presented in the course and how it relates to Quantum Mechanics. Elaborate.

Assessing Students' Preferences

Question 1: Given the boundaries "Hate" and "Love," where would the "Mathematical Formalism" or "Experimental Discussions" presented in the course fit on the Wavelength scale?

- Students generally prefer to learn quantum through experiments



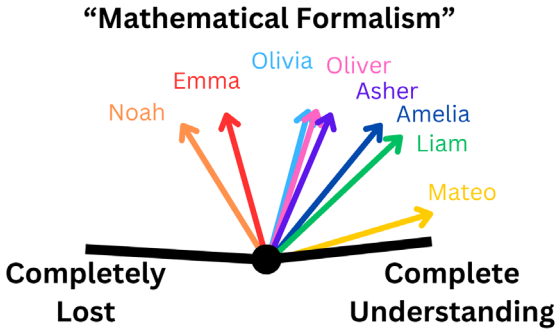


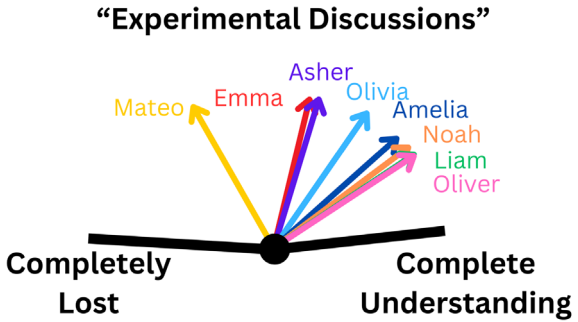
*"And I think the only thing I don't like about it is just that it just feels like abstract. **Sometimes it feels like abstract math.** Okay…And so there just needs to be a way to make that clear or see more. At least in the beginning, before we start really going to just the pure abstraction."*

Assessing Students' Self Perceptions

Question 2: Given the boundaries "Completely Lost" and "Complete Understanding," where would the "Mathematical Formalism" or "Experimental Discussions" presented in the course fit on the Wavelength scale?

- Looking at students' placements holistically, students perceive their mathematical and experimental understanding at approximately the same levels



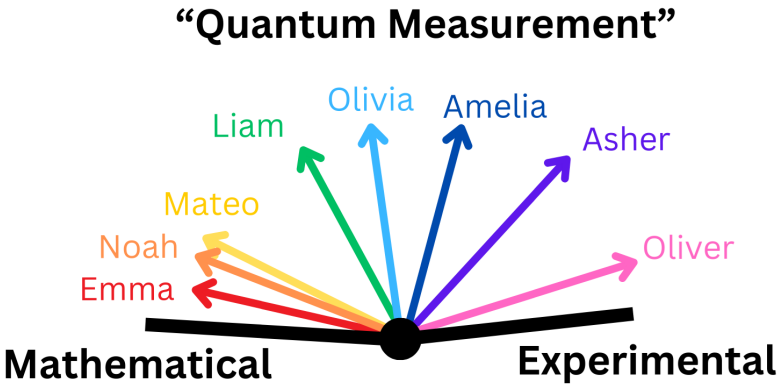


"So one cool thing was when I was doing homework for the double slit experiment…And like Stern -Gerlach, like my roommates would be there and was like, what's that? And I'd try to explain it to him. And I figured out that I actually could. ***Because I think of the tools that were used, the visuals and experiments, I could pretty much give like a decent overview of what's going on.*** *"*

Quantum Measurement: More Mathematical or Experimental?

Question 3: Given the boundaries "Mathematical" and "Experimental" where would "Quantum Measurement" fit on the Wavelength scale?

- Students are slightly more likely to associate Quantum Measurement with being more mathematical than experimental



"I think that like the measurement part makes the most sense in a ***physical experiment*** *. Like, I think I* ***have better experimentational descriptors of the measurement*** *part rather than like the, like the overall process."*

Experiment Verifies Theory

Question 4: How would you relate the idea of "Quantum Measurement" with the Mathematical Formalism or Experimental Discussions presented in the course and how it relates to Quantum Mechanics. Elaborate.

Experimentation	Mathematical Formalism
• Verification that the theory is correct • Shows the physical truth of the system • Highly practical/ applicational • Students struggled to explain provided examples as it related to Quantum Measurement	• Theory that explains why • Is a list of possibilities to be explored • Highly probabilistic • Students were good at explaining provided examples as it related to Quantum Measurement

*"Mean I guess… the Stern -Gerlach…like you just run the experiment to get to understand what's going on like with the spin states. **So it provides I guess kind of a proofs…it shows you how it proves that it does it …**."*

*"Hmmm….What does measurement and quantum measurement mean in experimentation? Well, I guess it would just be the same thing, right?...Yeah, it's just the same thing, but just with experiments. **I think (the mathematical formalism) was just more like learning conceptual and then experimentation was more practical.**"*

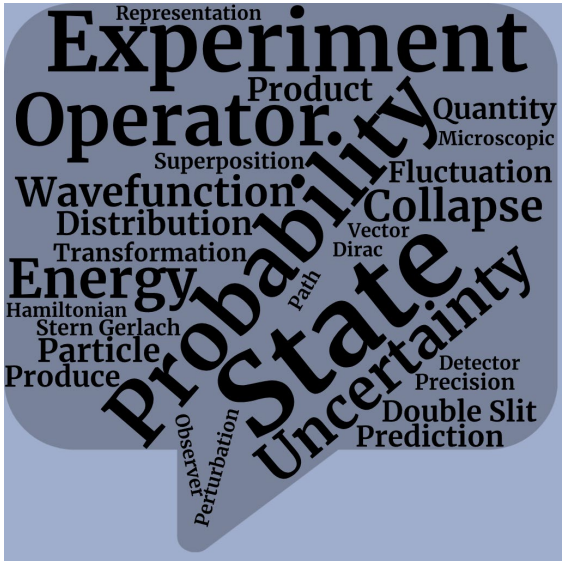
How Nuanced are Students Responses to Measurement?

When asked to relate measurement, students were more inclined to think out loud about experiments but not make an explicit response to the prompt

Relating Measurement to Experiments

"Like, when there's a quantum measurement, we definitely need to consider the ***Heisenberg uncertainty*** *. Or, like, we were… what comes to my mind is* ***perturbations*** *, or like* ***fluctuations*** *. Okay. Yeah. Like, that's what comes to my mind because I think of, like, I need to think about something mathematical in terms of the measurement."*

Relatings to Experiments	Relating to Mathematics
~800 words total	~1100 words total
~100 words per student	~140 words per student



Relating Measurement to Mathematical Formalism

Summary of Key Ideas

- Students taking an operator -based quantum mechanics class had strong levels of understanding of how the mathematical formalism relates to an important quantum concept

- Even though students generally preferred learning their quantum concepts through experiments, the students did not necessarily assess their experimental understanding to be higher than their mathematical understanding

- When students were asked to make connections, they relied heavily on their mathematical understanding and were not as comfortable with the conceptual ideas behind experiments even when they prefer learning through experimentation in a course with a conceptually -centered approach around simulations

- Ultimately, the interviewed students were still able to illustrate meaningful connections between these complex quantum concepts and their conceptual understanding of quantum measurement

Future Projects, Collaborators, and Funding

- 2nd Round of Undergraduate Interviews: Evaluating students' quantum knowledge on quantum optical experiments
- Fall 2025 will have next group of students taking Quantum both online and in - person at Georgetown
  - Surveys, Interviews, Evaluating Work
  - Focus on other quantum mechanical ideas like Superposition or Entanglement
- Evaluating online repository of students assignments for those who took *Quantum Mechanics For Everyone* and *Quantum Mechanics*

Collaborators: James Freericks and Leanne Doughty

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