When shown data from **quantum mechanics experiments**, students do not consider the influence of **experimental uncertainty**.

No room for error: Students' perception of measurements in quantum mechanics

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Abstract

- We tested **how students interpret the variability in data** from hypothetical experiments in classical and quantum mechanics through **semi-structured interviews**.
- In **classical mechanics** students considered the influence of experimenter error, limitations of the measurement equipment, and confounding variables.
- In **quantum mechanics** most students do not consider these influences but attribute variability to inherent uncertainty in quantum mechanics.
- Some students even explicitly say there are inherently fewer confounding variables in quantum mechanics and the equipment is more precise.

METHODS

- We **interviewed 20 students** from quantum mechanics and advanced lab courses at 2 institutions.
- **Students were shown possible experimental data** from one experiment in classical mechanics and one experiment from quantum mechanics.
- For each set of data **we asked questions** about the **variability in the data**, for example: "*Why does the distribution have the shape it does?*" or "*What would the histogram look like if measured by a scientist under the best possible conditions?*"
- We **coded different sources of uncertainty** that students talked about (inspired by Zwickl et al., 2015).

RESULTS

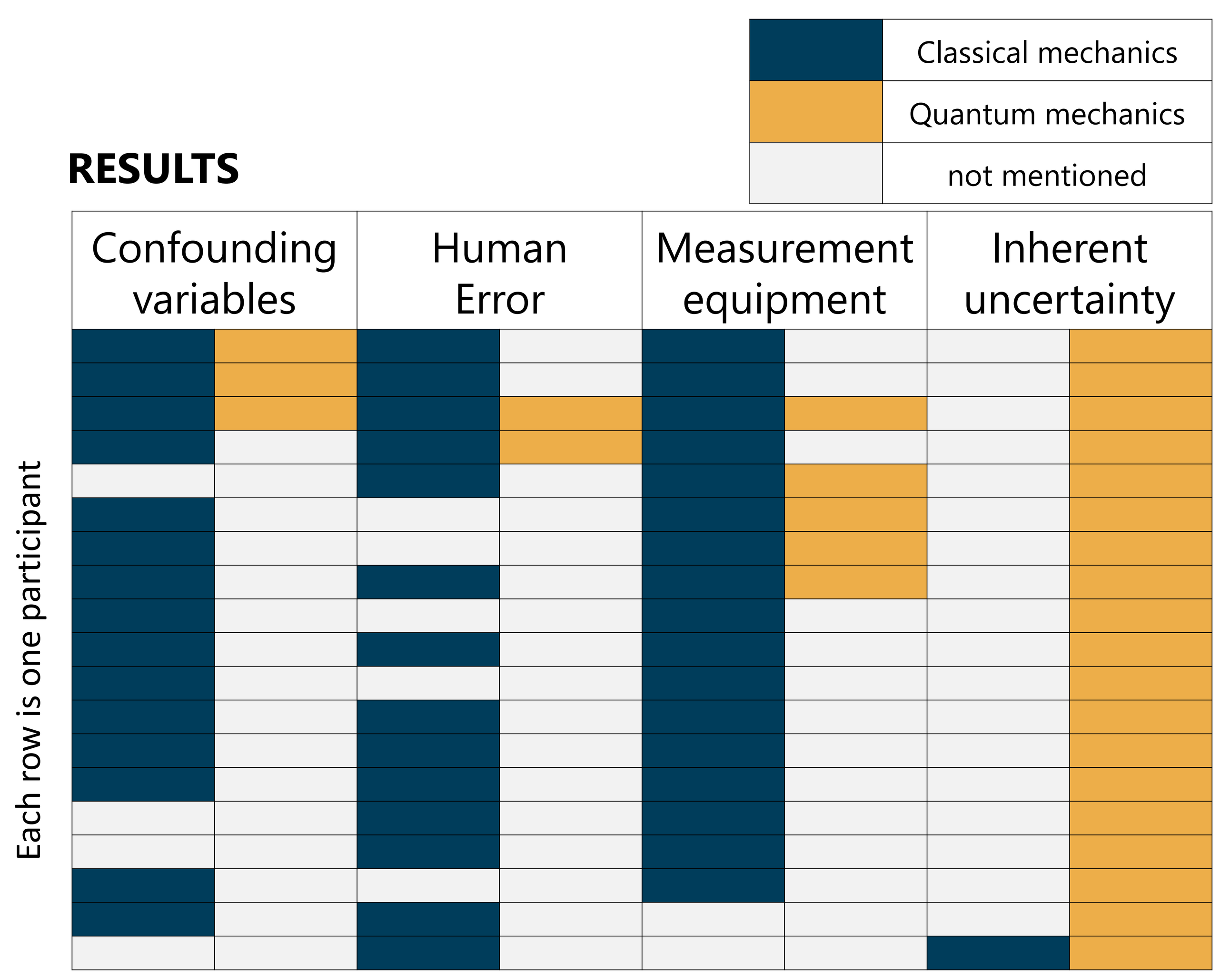

Fig. 4: Sources of uncertainty mentioned by each participant in each context. For example, the first participant mentioned confounding variables in QM and CM, human error in CM, measurement equipment in CM, and inherent uncertainty in QM.

- Most students make **generic statements about inherent uncertainty** in QM, e.g. that QM is inherently probabilistic, Heisenberg uncertainty principle or wave-particle duality.
- Some students explicitly say **there is less experimental uncertainty in quantum mechanics**

DISCUSSION

- Students interpret the variability in the same set of data very differently depending on the context.
- In our interviews, students evaluated **quantum** mechanical variability from an **abstract, theoretical perspective**, rather than considering the experimental setup.

Interview protocol

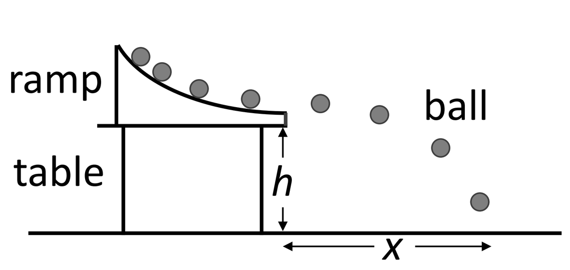

Fig. 1: Sketch of classical mechanics experiment (from Allie et al., 1998).

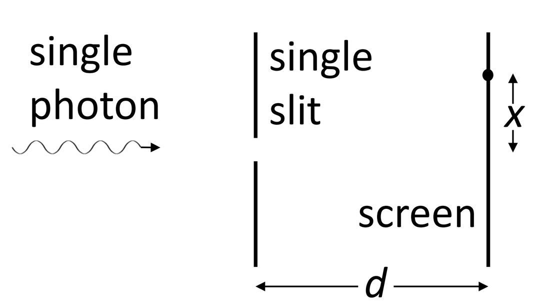

Fig. 2: Sketch of quantum mechanics experiment.

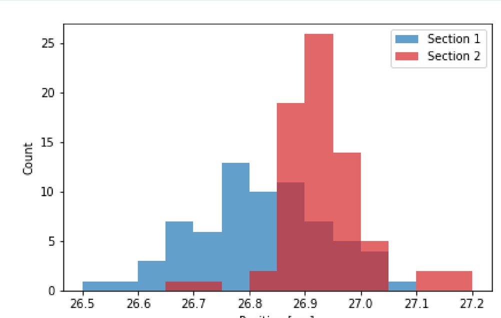

Fig. 3: Experimental data from both experiments that students see.

Leave notes on student quotes

yes it *DOES* rhyme
Thank you for coming closer.

How do these students characterize uncertainty?

Participant X:

What comes to your mind when you think about measurement uncertainty in classical mechanics in general?

-- literally nothing. It's not something I've thought about before. Um, yeah, it's never seemed like something that's all that important. Um, you know, it's, again, we're doing it with a system like this, then a variation of, you know, less than two centimeters isn't important necessarily, but it's always there. Like there's no way to completely get rid of it. We're using imperfect tools. Um, yeah.

What comes to your mind when you think about measurement uncertainty in quantum mechanics?

-- That I don't remember what it is. Um, I know quantum mechanics is probabilistic theory. I know that anytime we take a measurement, we have certain possibilities of getting discrete values that we can calculate, what those probabilities are if we have an equation of state. But in terms of uncertainty in those measurements, I really don't know, cause it seems like every time we do, uh, quantum problem, granted I haven't done quantum in like a year. Um, but when we do these problems, we're thinking about what possible values are. So say we have some system and we are asked to measure the spin in the z or the possibility of measuring spin up in the z direction. Right. Um, and then if we actually did the measurement and we did measure spin up in the z direction, it's certain. Like that is what the state is at that moment in time when we make the measurement and assuming that is an Eigenstate of our Hamiltonian, then that state doesn't change. Um, and, so classically I'd say there's more, well there is uncertainty in all classical measurements, but the way I understand it is that quantum measurements there isn't in most of them I'm hesitant to say all of them. MMM. The things we can know simultaneously there isn't.

Participant Y:

What comes to your mind when you think about measurement uncertainty in classical mechanics in general?

-- So classical mechanics, classical mechanics, it's, more of like assuming like a spherical cows in vacuums and frictionless vacuums, it'd be like different changes in like starting value would for propagate and change, the resulting value of whatever you're measuring. So like in the slopes would a change in the starting position would change the ending position.

What comes to your mind when you think about measurement uncertainty in quantum mechanics?

-- So quantum mechanics is like two edges to that sword. Just like, how good an experiment you can make and how good an experiment nature will allow you to make. You can only make, you could only like, know so much about a quantum mechanical system, supposed to uh a classical system such that, uh, sort of limited in how good of data you can get. So, uh, LIGO for example has, has, uh, a sort of quantum mechanical limit on how well they can measure because the mirrors aren't that zero degrees Kelvin. It would decrease in that, uh, the mirrors aren't in zero Kelvin, so there's some thermal noise making that sort of bouncy uncertainty. So if I were to make like mere zero K and not zero K [sketches flat and "wobbly" mirror surface], okay. It'd be sort of weakly on some like pseudo quantum mechanical level. So it'll bounce off there nice and wonderfully, but uh, that's not gonna make a wonderful measurement.

Participant Z:

What comes to your mind when you think about measurement uncertainty in classical mechanics in general?

-- Um, in classical mechanics, I think measurement uncertainty is, is based on the setup of the experiment or the use of the experiment, user error, systemic error errors in measurement, um, just not being able to completely eliminate any erratic variables.

What comes to your mind when you think about measurement uncertainty in quantum mechanics?

-- Um, it's expected. It's what you want to see. If you're not getting measurement uncertainty, then something's going wrong.

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