All of the responses to the questions below are coded as P (Principles), L (Limitations), S (Statistics), and O (Other).

PM, SS, BM, SG designate the experimental scenario associated with the response. These can be ignored for the first pass of making centroids.

You can read about the experimental scenarios in <https://journals.aps.org/prper/pdf/10.1103/PhysRevPhysEducRes.19.020157> (Fig. 1).

**Question 1: Sources**

Question text: Students in a lab section set up the experiment and measure *d*. They collect 50 data points. The TA combines the measurements into a histogram. What is causing the shape of the distribution measured by the students? List as many causes as you can think of.

Student survey response in “Response”, corresponding code in “code”. Codes are P,L,S, and O (other). Example responses for each code below.

P Centroid

*Principles*

* “Randomness of brownian motion”
* “Nature of Brownian motion results in a natural distribution”
* “Spins should be random”
* “quantum effects in electrons”
* “They’re still going to see a wave pattern even in 1 experiment”
* “No, it’s a diffraction experiment, even with perfect equipment, we can’t tell where electrons will land before they do”
* The diffraction of the electron wave function going through the slit
* “At some point, the distance being measured is in the Quantum Scale, where nothing is ever certain.”
* “Quantum mechanics is probabilistic, so there is inherent variation in the experiment”
* “In quantum mechanics, the world is basically (in most interpretations) probabilistic and has a certain degree of randomness to it. Thus many of the processes in experiments have a theoretical uncertainty that cannot be reduced by any means.”
* “Quantum mechanics has inherent probabilities.”
* More or less supposed to be there since QM is a statistical field at the scale that we care about
* “the fact that the movement of particles at the fundamental level is random; the wideness of the distribution should obey Heisenberg Uncertainty Principle”
* “Heisenberg's Uncertainty Principle -- being certain in one variable leads to less certainty in the other variable (eg. position and momentum). Also the generalized uncertainty principles for any two observables.”
* “(the Heisenberg uncertainty principle) delta x times delta p = hbar/2 There's also the energy-time relation”

L Centroid

*Limitations*

* “Ball not placed at the right spot each time”
* “the placement of the magnet might shift from time to time”
* “Different ramps cannot be identical”
* “Materials issues (ball; ramps are identical)”
* “the electron source’s release velocity of the electrons”
* “the effect of the space between the slit and the screen on the electron (air resistance? friction? etc)”
* “the time may not be exact”
* “Meterstick not held correctly”
* “There should be a bimodal distribution maybe students are faking data”
* “Ruler isn’t accurate enough in micrometer range”
* “a ruler is not a suitably-precise instrument for this task”
* “Difficulty in spotting the dropped place because of the ball bouncing up again at the floor”
* “The small number of measurements resulted in the uneven histogram”
* “student rounding”
* Human error
* “Measurement uncertainty in classical mechanics can usually arise from human error in setup or calculation.”
* “Human error, especially in the manufacturing of the experimental apparatus”
* “Human error (things like timing a stopwatch, measuring with a ruler, etc.)”
* Quotes related to the water droplet and microscope for Brownian motion
* “Tapping the microscope or other jitters from the outside world.”
* “the initial placing of the particle”
* “difference in particle characteristics (size, energy, etc)”
* “Differences in distribution of particles in water between students”
* “Different microscope (focal lengths)”
* Generic statements about the equipment generally (but not specific pieces of equipment)
* “environmental influences”
* “non-ideal effects like friction.”
* “small changes in initial conditions”
* “Uncertainties in measurement apparatuses (i.e. gradations on a ruler, etc.)”
* “Mostly brought about by minor differences in equipment”
* “I think of it as some sort of limitation of instruments, variance caused by imperfect equipment.”
* “changes in the environment like air flow”

S Centroid (encoded in spreadsheet as P + Ms or O + S)

*Statistics*

* “Multiple random measurements result in a gaussian distribution”
* “The overall distribution is like a Gaussian, which makes sense. Because there is error in measurement.”
* “And \*possible\* statistical errors: from very large sample sizes”
* “Random statistical variation”
* “Minor statistical randomness”
* “Statistics”
* “Normal distribution”
* “Central limit theorem”
* “bell curve due to normal distribution and similar conditions for every experiment”
* “That just looks like the average curve of results.”
* “Natural statistical variation that arises from taking measurements so there is some spread.”
* “The shape is the normal distribution, it is expected to occur in a series of random trials”

“Other” or “Irrelevant” code: no centroid. Ideally, codes with the O label would fall outside the regions of the other centroids

**Question 2: Generic classical and Question 3: Generic quantum**

Question 2 text: What comes to mind when you think about measurement uncertainty in classical mechanics?

Question 3 text: What comes to mind when you think about measurement uncertainty in quantum mechanics?

Responses to these two questions can have multiple ideas. The coded responses have been manually segmented. The segments are in “Segmented\_Response” and the code associated with the segment is in “code”. C/Q denotes if the segment comes from their response to Generic Classical/Generic Quantum. “n” gives the number of the segment in the response. The same response ID appears in multiple rows if the responses have multiple segments.

The students’ full responses to Question 2 and Question 3 are in Response\_Generic\_Classical and Response\_Generic\_Quantum. These columns may or may not need to be used.

Data from 20-21 appears first in the spreadsheet. It is segmented and coded. Uncoded data from 21-22 appears later in the spreadsheet.

The coding scheme for Sources (Question 1 above) was imposed on the data for this question. The first thing we should try is to apply the centroids/regions for Sources onto the data here.

**Question 4: More**

If the students performed the experiment and collected 100 data points instead of 50 using the same equipment, how would the shape of the distribution change?

* Distribution stays roughly the same.
* Distribution becomes wider.
* Distribution becomes narrower.
* A single value is measured.

Please explain your reasoning.

Student written responses are in “More\_explanation”. “More\_response” contains their answer to a related multiple choice question with 4 options. Codes are in “P\_more”,”L\_more”, and ”S\_more”. For this question, a single response is allowed to be in multiple codes.

Codebook: More Better Codebook\_updated\_for\_clustering.docx

P Centroid (PP)

* “Chaotic motion is inherent to the system”
* “The motion is random, so it does not matter how many trials are taken.”
* “Same as above. Distribution is not due to error, but is natural part of brownian motion.”
* “There will always be uncertainty in position and momentum due to Heisenberg Uncertainty Principle”
* “More data will not alter the probability function of the particle.”
* “Quantum probability distribution likely dominates the shape of the distribution more than experimental errors - will not change with better equipment / more trials.”
* “As you increase the number of iterations your system should converge to the proper solution which should be one solveable value for a kinematic problem.”

L Centroid (PL)

* “Since the equipment is the same, the systematic errors should be similar. Presumably the other variables are the same (Temp), so statistical errors are similar as well. Thus the distribution is similar.”
* “The distribution should be roughly Gaussian with the same width because they are using equipment with roughly the same error and uncertainty.”
* “Standard deviation remains fixed, unless the methodology is changed.”
* “It will depend some on how well the new student's perform the experiment, but if they follow the same procedure as the first 50 students, they will get something similar to the first 50 students.”
* “If the students don't work to eliminate or diminish the human error variable, then there will be a wider range of answers. Thus, the distribution will become wider.”
* “More students will just keep introducing errors, so I don't think the distribution would get all that much narrower.”

S Centroid (S)

* “A sample size of 50 is already statistically enough to infer a normal sample distribution. Therefore more samples will just smooth out this distribution keeping the same mean and standard deviation.”
* Increasing n should not change the distribution since n is already large
* There's already a sort of bell curve taking shape; if anything the 100 more students would help smooth out that curve and keep distribution roughly the same.
* The new students will increase the 'resolution' and details of the distribution, but not drastically change the shape.
* On average, the measurements from all the students will be distributed similarly randomly. The sum of these will still average to roughly the same distribution.
* “If there is a true value of x, then distribution would become narrower because of how most data points should trend to the true value of x. there will still be less points on the sides”
* “a greater sample size reduces the impact individual measurement errors and other non-consistent factors”
* More data added to the set should increase the confidence level of the results.
* “With more data points added, the outliers will have less "pull" on the histogram. They will still be there but much less prominent, and most points should land closer to x, causing a gaussian distribution”
* “We have a higher probability of reaching the central position than the rest, so more students would reach that the the distribution would become narrower. Ideally a single value is measured.”
* “we expect variance to grow more slowly than peak height.”
* “hopefully they all perform the experiment well and the law of large numbers kicks in, so the data approaches the theoretical prediction.”
* “Larger sample size means smaller distribution”

“Other” code: no centroid. Ideally, codes with the O label would fall outside the regions of the other centroids. V stands for vague.

**Question 5: Better**

If experts performed the experiment and collected 50 data points using the best possible equipment, how would the shape of the distribution change?

* Distribution stays roughly the same.
* Distribution becomes wider.
* Distribution becomes narrower.
* A single value is measured.

Please explain your reasoning.

Student written responses are in “Better\_explanation”. “Better\_response” contains their answer to a related multiple choice question with 4 options. Codes are in “P\_better”,”L\_better”, and ”S\_better”. For this question, a single response is allowed to be in multiple codes.

P Centroid (PP)

* “The experiments of experts don't follow different physics.”
* “If the scattering is inherently physically probabilistic, then better equipment won't change our expectation of the distribution.”
* “The uncertainty is not due to equipment, but rather an inherent uncertainty from Heisenberg Uncertainty Principle.”
* “Because you can't perfectly know the position of a quantum mechanical particle”
* “Quantum probability distribution likely dominates the shape of the distribution more than experimental errors - will not change with better equipment / more trials.”

L Centroid (PL)

* “If consistent variables are used, such as the angle and height, then there will be a smaller range of answers, so the distribution will become narrower.”
* “typically we'd expect reducing the effect of confounding factors in an experiment to bring our measured values closer to our classical prediction (which would predict a single value)”
* “Since this is a classical system, our uncertainties come from our measurement equipment etc. If we were to get the best equipment, our measurements would become more accurate and thus the distribution would become a bit more narrow.”
* “Physics is deterministic, if the experts have great equipment whose precision is higher than the error we can perceive, then we can just measure one value each time.”
* “im assuming experts would perform the experiments more accurately so the distribution will generally stay the same even when performed 100 times”
* “With better equipment and more experience, the distribution should be more consistent and thus narrower.”
* “Because the experts are using better equipment, there will inherently be less uncertainty if used correctly (assuming the experts know how to operate the equipment so as to have the best possible performance). Since this is the case, the distribution should become narrower as the measurements become more precise and start to agree more on a mean value.”

S Centroid (S)

* “doesn't matter who performs the experiment; just statistics.”
* “bell curve”
* “Same reasoning as in the previous part - the distribution would likely become more narrow than with the students, but both will decrease as the sample size increases”
* “Central limit theorem”
* “Without as many outliers, the distribution tighten.”
* “The more data the greater the distribution”

“Other” code: no centroid. Ideally, codes with the O label would fall outside the regions of the other centroids.