"What's the right answer?"

Doubt, Uncertainty, and Provisional Truth in Science

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The Roxbury Latin School

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"What's the right answer?"

- Our goals - Teaching students how to learn from observations
- Philosophy - Embracing uncertainty
- History - Accepting uncertainty
- Teaching - Illustrating uncertainty
  - Measuring Pi (Exercise)
  - Illustrating accuracy, precision and systematic error
  - Putting student data in context

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Philosophy - Richard Feynman

"When a scientist doesn't know the answer to a problem, he is ignorant. When he has a hunch as to what the result is, he is uncertain. And when he is pretty darn sure of what the result is going to be, he is still in some doubt....

Scientific knowledge is a body of statements of varying degrees of certainty - some most unsure, some nearly sure, but none *absolutely* certain."

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Philosophy - Richard Feynman

“It is our responsibility as scientists... to teach how doubt is not to be feared but to be welcomed and discussed; and to demand this freedom as our duty to all coming generations.”

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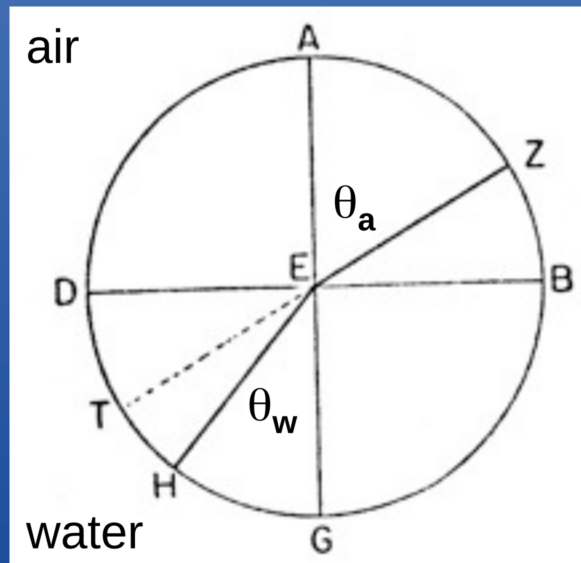
Imposing Patterns on Observations

Ptolemy investigated optics as well as astronomy and wrote what may be the first “lab report” with measurements of refraction between air and water.



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Imposing Patterns on Observations

- Consider Ptolemy's data in the table.
- θ_a = angle from surface normal to light ray in air θ_w = angle from surface normal to light ray in water
- Do you see the pattern?
- Without a physical explanation, Ptolemy imposed a numerical pattern on the data.

θ_a	θ_w
(deg)	(deg)
0	0
10	8
20	15½
30	22½
40	29
50	35
60	40½
70	45½
80	50

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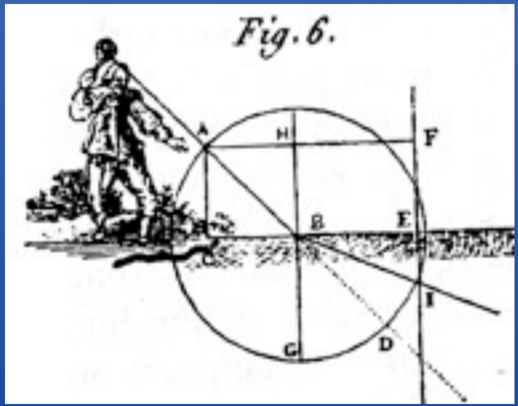
Imposing Patterns on Observations

Descartes advocated a philosophy of doubt but had little doubt in his own explanations such as his refraction model from *Optics*:



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Imposing Patterns on Observations

With his (spurious) physical model, Descartes supported a different pattern:

$$\frac{\sin\theta_a}{\sin\theta_w} = \text{constant} = 1.33$$

θ_c in the table is computed from this equation.

θ_a	θ_w	θ_c	$\Delta = \theta_w - \theta_c$
(deg)	(deg)	(deg)	(deg)
0	0.0	0	0
10	8.0	7.50	0.50
20	15.5	14.90	0.60
30	22.5	22.08	0.42
40	29.0	28.90	0.10
50	35.0	35.17	-0.17
60	40.5	40.63	-0.13
70	45.5	44.95	0.55
80	50.0	47.77	2.23

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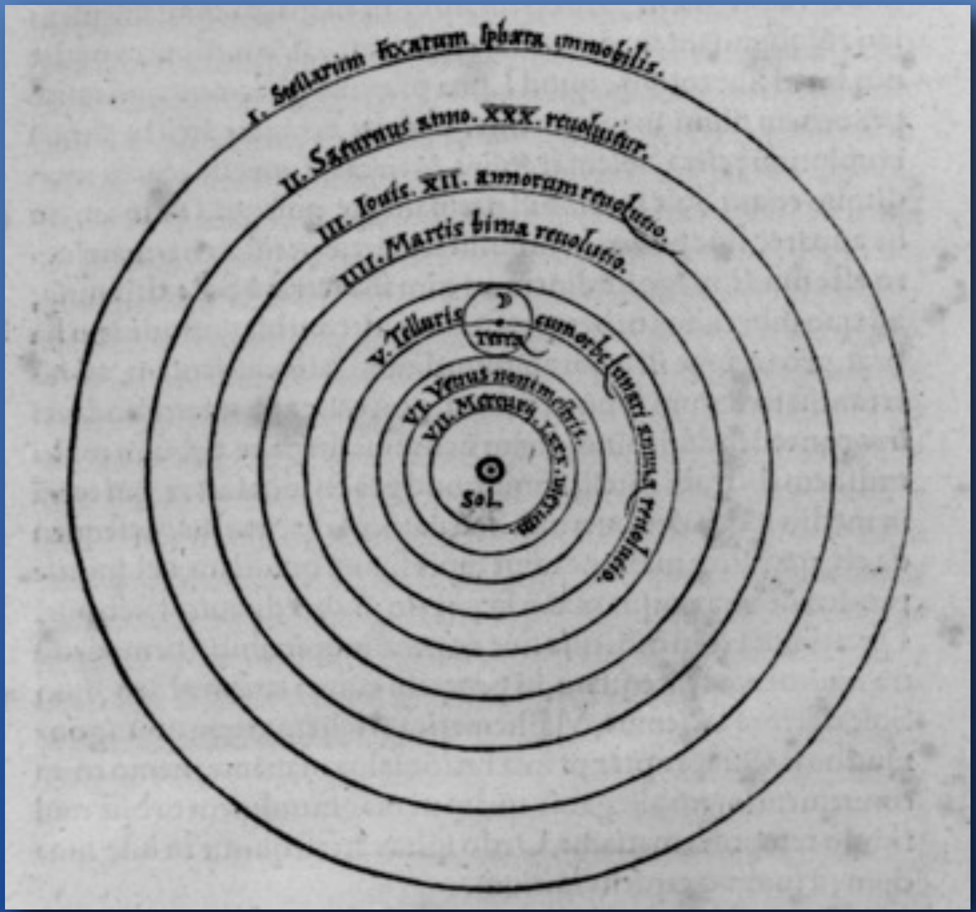
Imposing Patterns on Observations



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Letting the Data Do the Talking

Tycho Brahe made multiple measurements with multiple large instruments and multiple observers to assess the uncertainty of his observations

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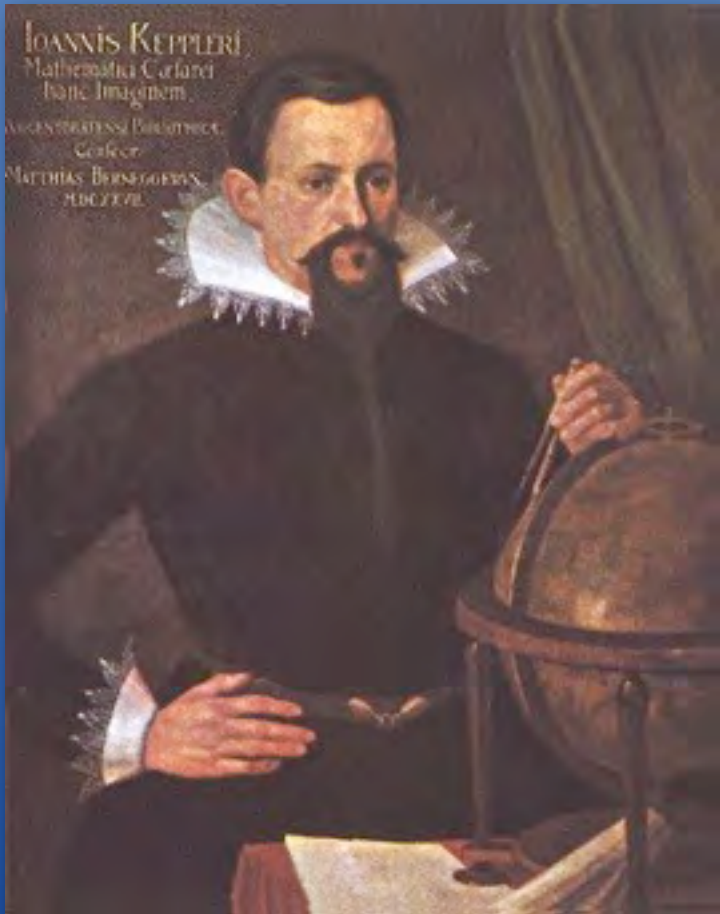
Matching Theory to the Data



"...by divine kindness [we] were given an accurate observer such as Tycho Brahe....For, if I had believed that we could ignore these eight minutes, I would have patched up my hypothesis accordingly. But since it was not permissible to ignore them, those eight minutes point the road to a complete reformation of astronomy."

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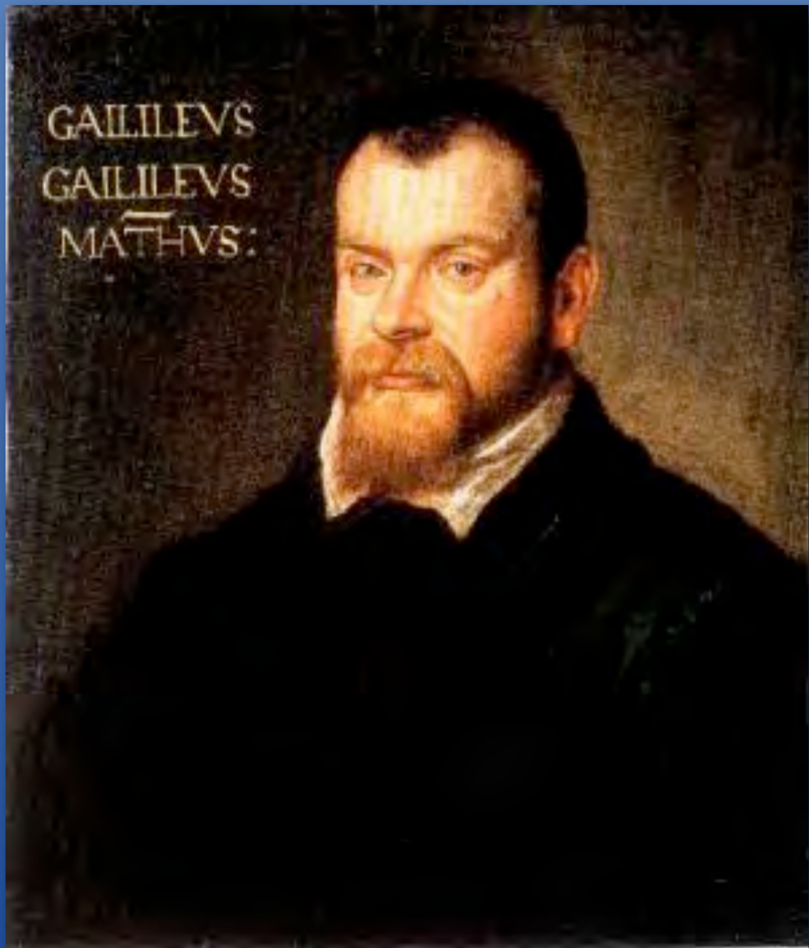
Allowing for Uncertainty



"I ... who have made the test can assure you that a cannon ball weighing one or two hundred pounds, or even more, will not reach the ground by as much as a span ahead of a musket ball weighing only half a pound, provided both are dropped from a height of 200 cubits."

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If the theory fits...

Newton's gravitation law strained credulity for many scientists because he offered no mechanism and seemed to imply action at a distance:

$$F_{grav} = \frac{Gm_1m_2}{r^2}$$

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If the theory fits...

Newton’s Rules for the Study of Natural Philosophy

- <u>Rule 1 – Simplicity</u> (appeared in *Principia* 1st edition)
  “No more causes of natural things should be admitted than are both true and sufficient to explain their phenomena.” (Ockham’s Razor)

- <u>Rule 2 – Uniformity</u> (appeared in *Principia* 1st edition)
  “Therefore, the causes assigned to natural effects of the same kind must be, so far as possible, the same. Examples are the cause of respiration in man and beast, or the falling of stones and America, or of the light of the kitchen fire and the sun, or the reflection of light on our earth and the planets.”

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If the theory fits...

- Rule 3 – Universality (appeared in 2nd edition)
  "*Those qualities of bodies that cannot be intended and remitted [i.e., qualities that cannot be increased or diminished] and that belong to all bodies on which experiments can be made should be taken as qualities of all bodies universally.*"
- Rule 4 – Provisional Truth (appeared in 3rd ed.)
  "*In experimental philosophy, propositions gathered from phenomena by induction should be considered either exactly or very nearly true notwithstanding any contrary hypotheses, until yet other phenomena make such propositions either more exact or liable to exceptions.*"
  (I. Bernard Cohen and Anne Whitman, trans.)

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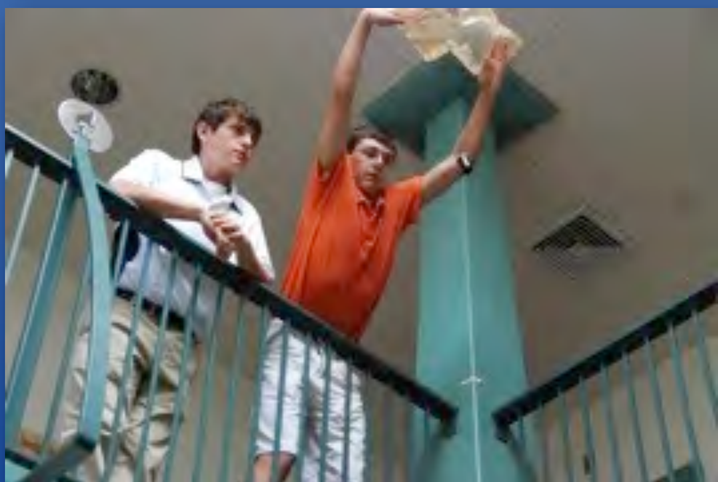
How do we introduce students to scientific uncertainty?



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An exercise

- Please measure the **diameter** and **circumference** of as many of the provided objects as you can in the next 10 - 15 minutes.
- Measure to the nearest 0.01 cm (0.1 mm).
- Report your observations to me when you've finished.

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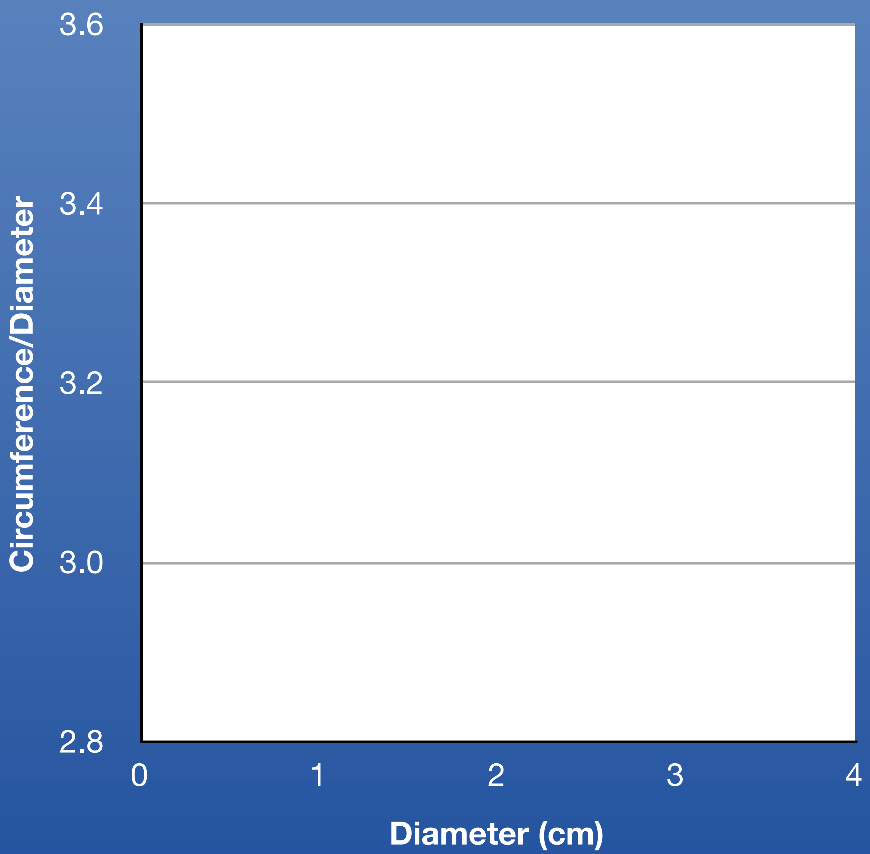
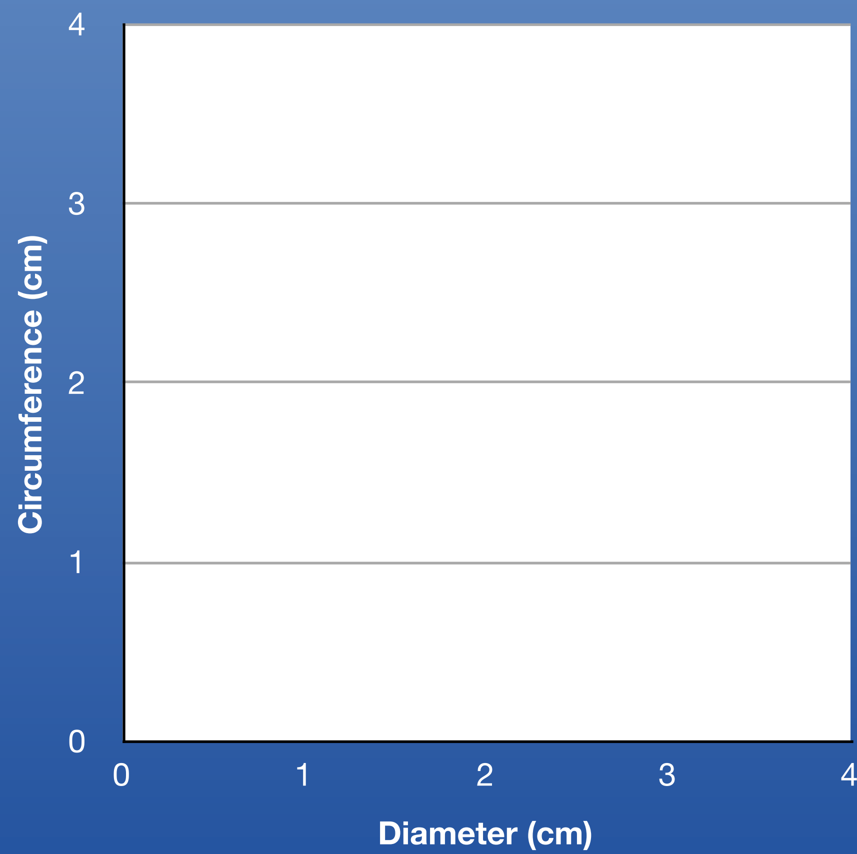
An exercise





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Accuracy, Precision, and Systematic Error

The Goal

Determine the density of 21.5 ml of water using an electronic balance and whatever container I give you.

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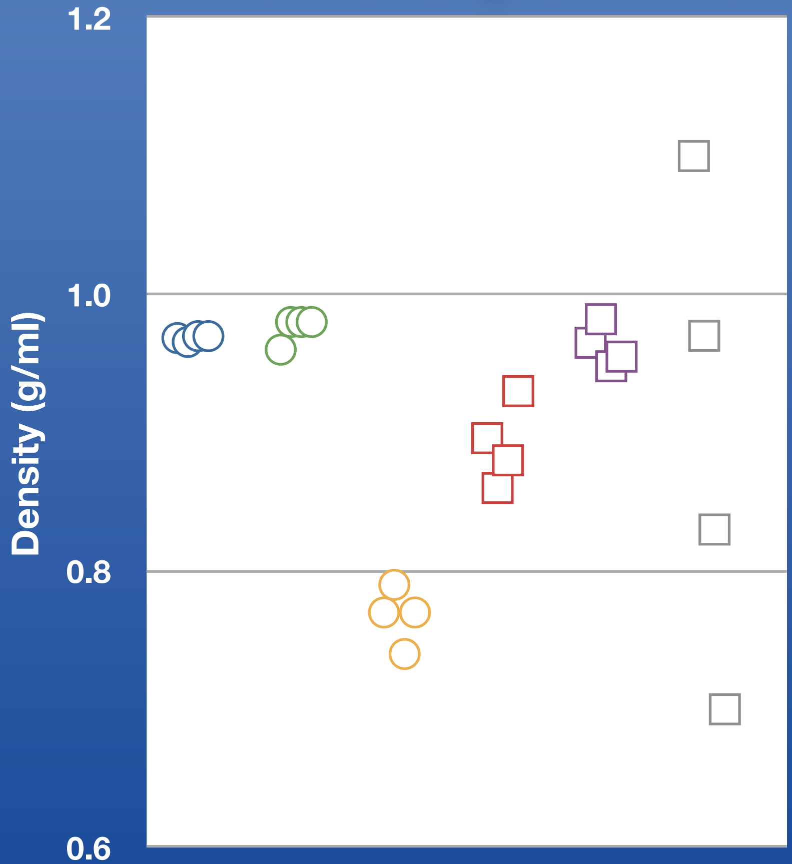
Accuracy, Precision, and Systematic Error

The Density of “21.5 ml” Water



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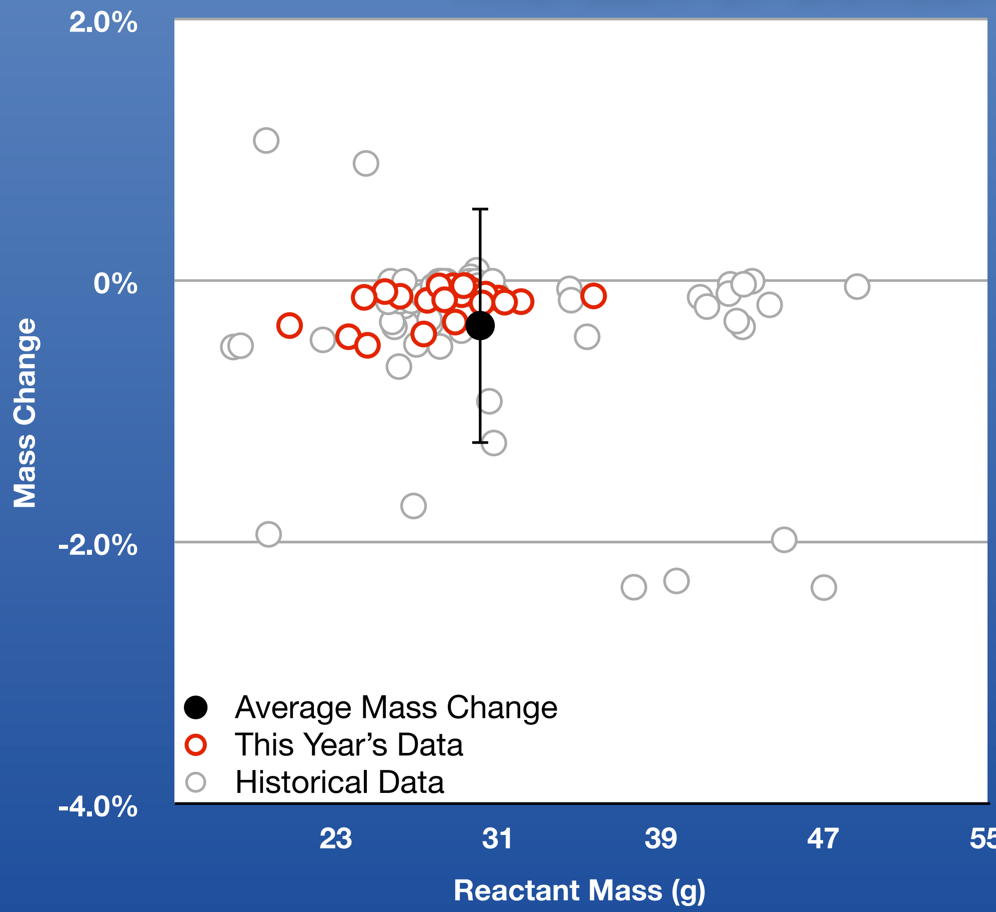
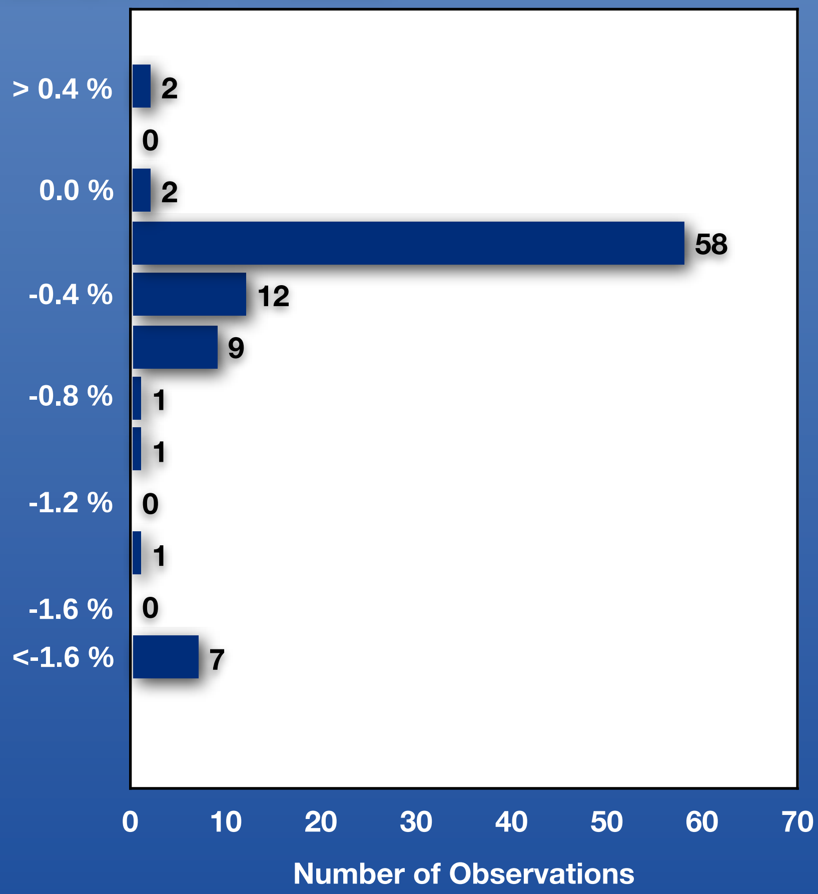
Data in Context: IPS

The Law of Conservation of Mass





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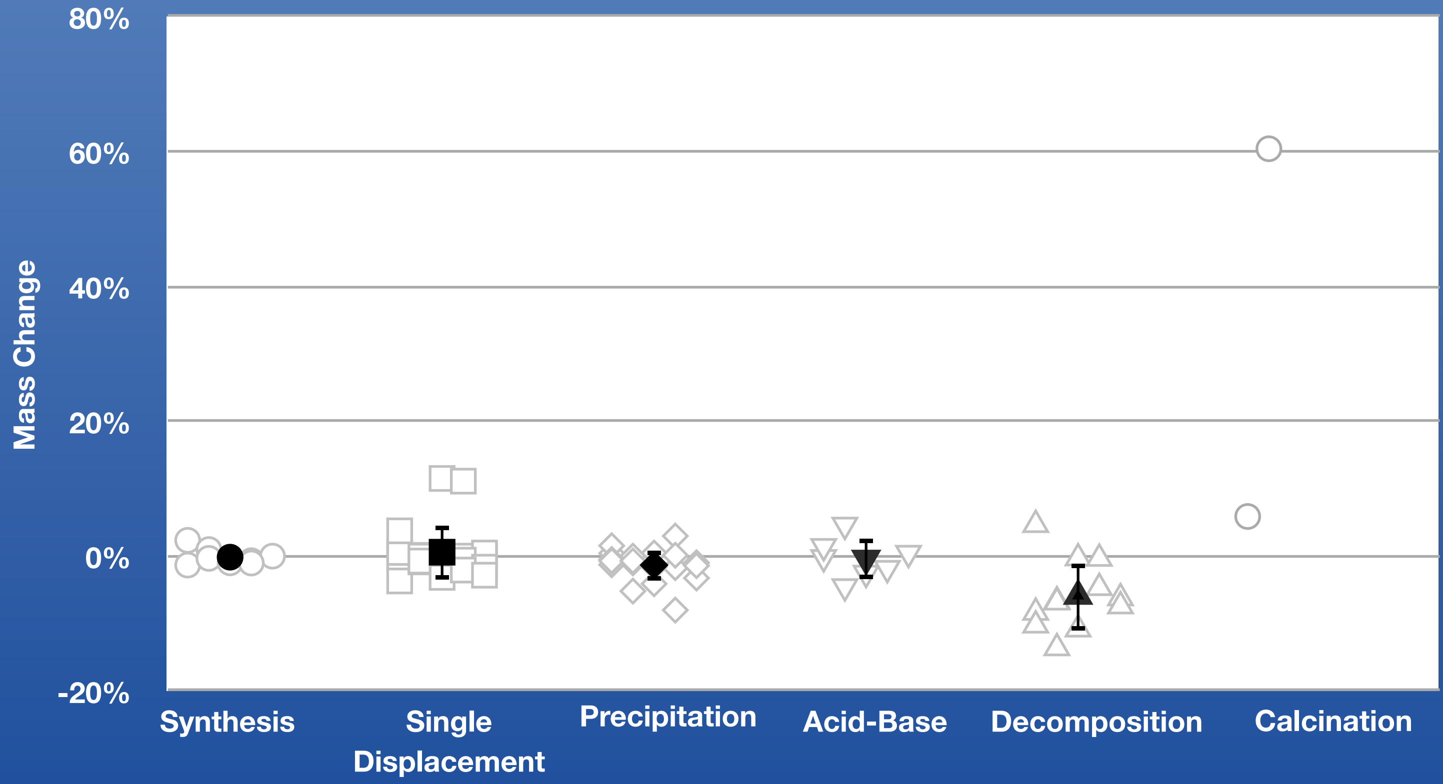
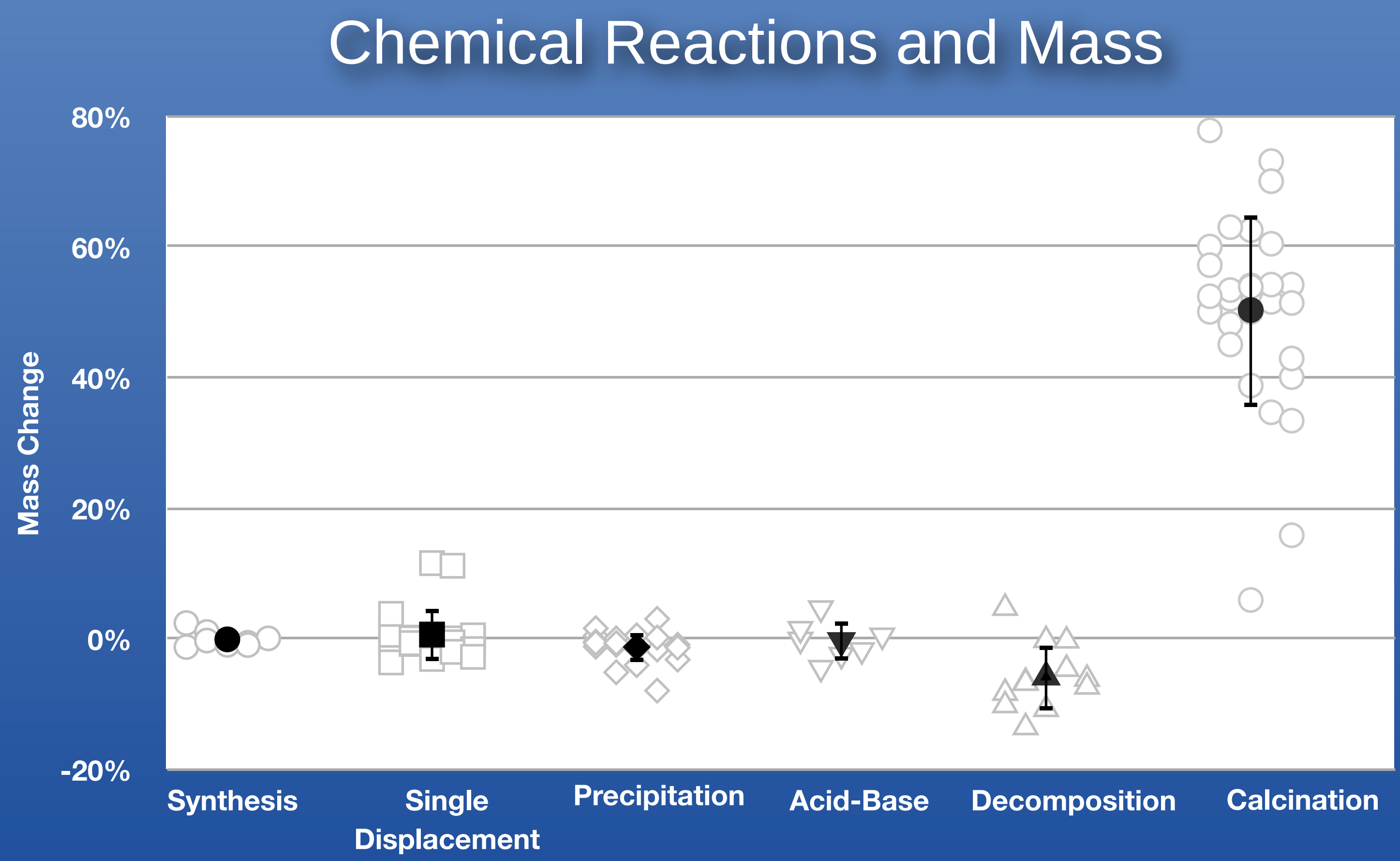
Data in Context: Chemistry

Chemical Reactions and Mass



Data in Context: Chemistry



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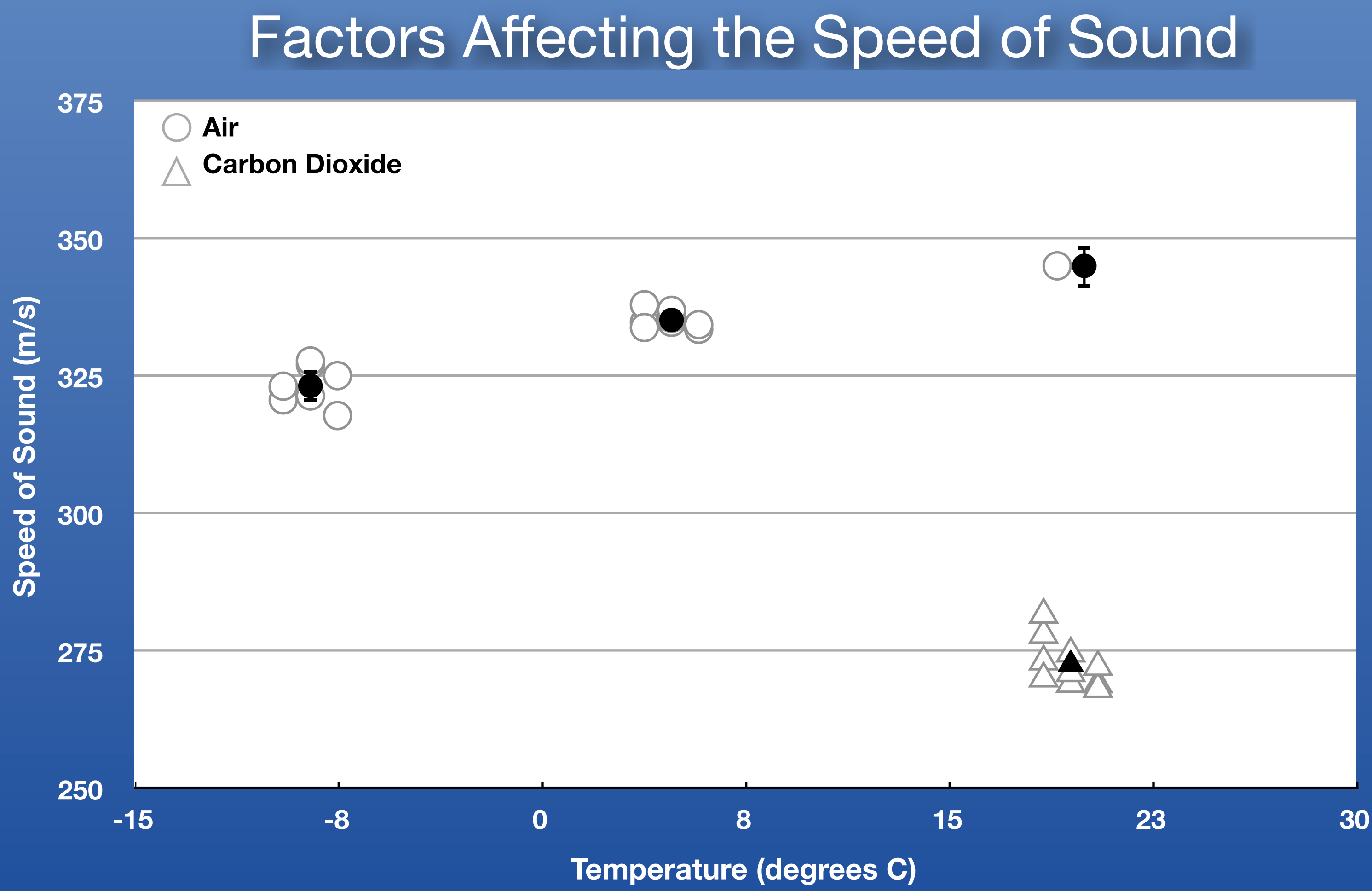
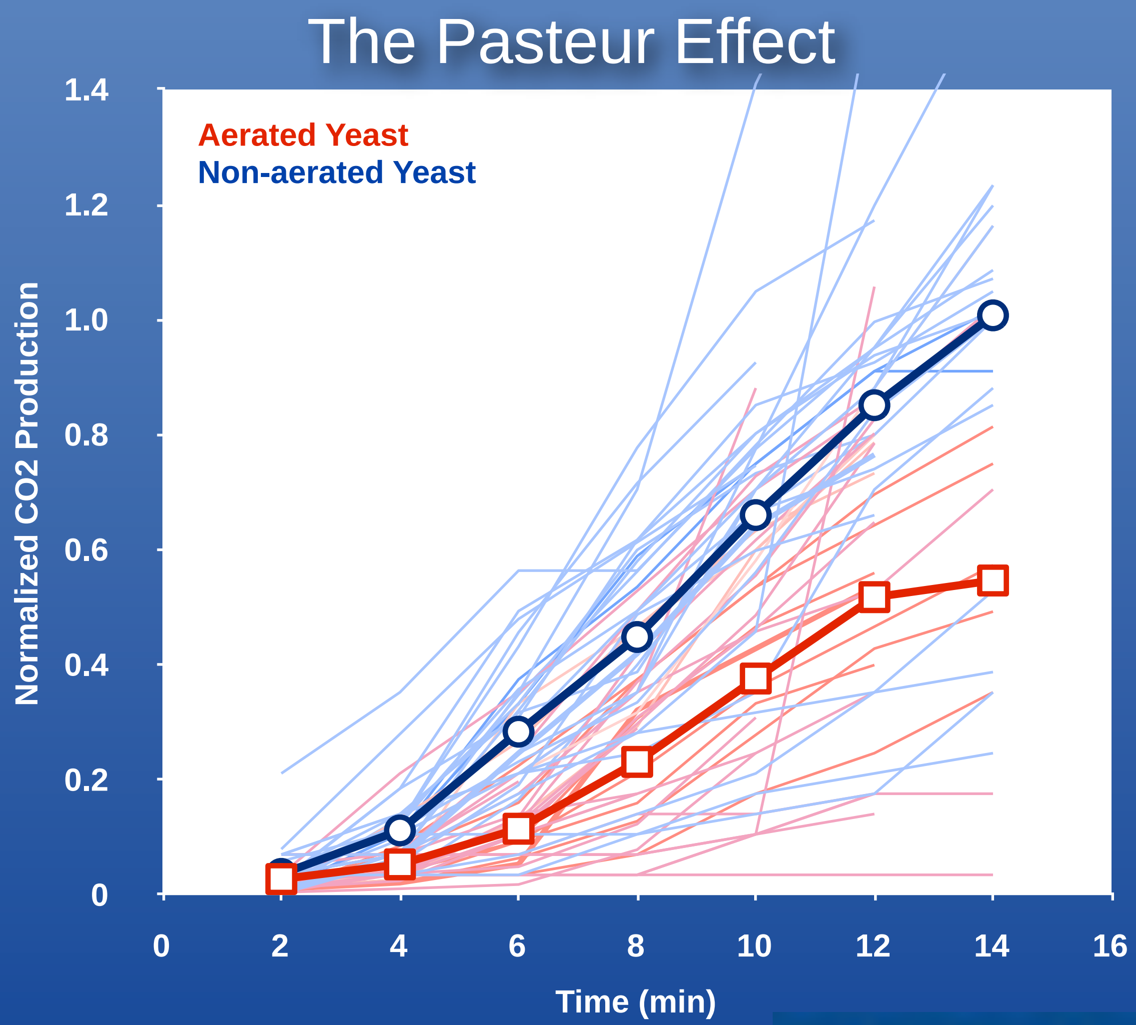
Data in Context: Physics



Data in Context: Biology



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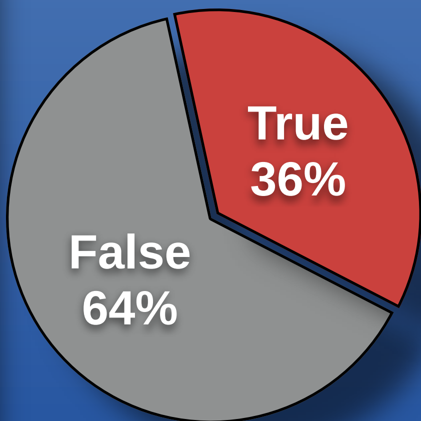
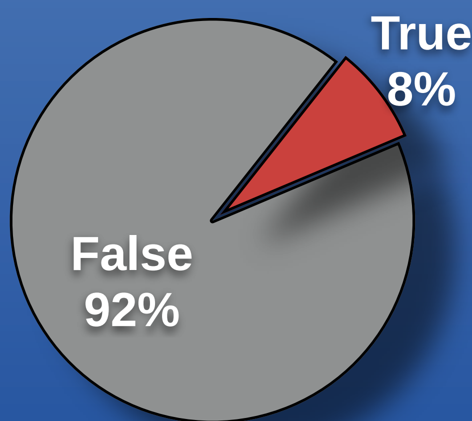
Do they get it?

Beginning of the year survey:
The scientific method eliminates all uncertainty.

Seventh Grade



Twelfth Grade



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Philosophy - Richard Feynman

“I think we must frankly admit that *we do not know*….This is the philosophy that guided the men who made the democracy that we live under. The idea that no one really knew how to run a government led to the idea that we should arrange a system by which new ideas could be developed, tried out, and tossed out if necessary, with more new ideas brought in - a trial-and-error system.”

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References

Feynman quotes are from the 1955 autumn meeting of the National Academy of Sciences published in R. P. Feynman, *"What Do You Care What Other People Think?" Further Adventures of a Curious Character*, Bantam Books, New York, 1989, pp. 240-248.

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- The Galileo quote is in G. Galilei, *Two New Sciences*, H. Crew and A. De Salvio, trans., reprinted by Dover Publications, Inc., New York, originally published by The MacMillan Company, 1914, p. 62.
- Newton's Rules are in *The Principia: Mathematical Principles of Natural Philosophy*, I. B. Cohen, Anne Whitman, J. Budenz trans., University of California Press, 1999.
- Student Photos: Mike Pojman
- Campus Photo: Andrew Katz

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