“What’s the right answer?”
Doubt, Uncertainty, and Provisional Truth in Science

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The Roxbury Latin School
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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"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."
“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.”
Ptolemy investigated optics as well as astronomy and wrote what may be the first “lab report” with measurements of refraction between air and water.
Imposing Patterns on Observations

• Consider Ptolemy’s data in the table.

• $\theta_a =$ angle from surface normal to light ray in air $\theta_w =$ 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.

<table>
<thead>
<tr>
<th>$\theta_a$ (deg)</th>
<th>$\theta_w$ (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>20</td>
<td>15½</td>
</tr>
<tr>
<td>30</td>
<td>22½</td>
</tr>
<tr>
<td>40</td>
<td>29</td>
</tr>
<tr>
<td>50</td>
<td>35</td>
</tr>
<tr>
<td>60</td>
<td>40½</td>
</tr>
<tr>
<td>70</td>
<td>45½</td>
</tr>
<tr>
<td>80</td>
<td>50</td>
</tr>
</tbody>
</table>
Descartes advocated a philosophy of doubt but had little doubt in his own explanations such as his refraction model from *Optics*.
Imposing Patterns on Observations

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

\[
\frac{\sin \theta_a}{\sin \theta_w} = \text{constant} = 1.33
\]

\( \theta_c \) in the table is computed from this equation.

<table>
<thead>
<tr>
<th>( \theta_a ) (deg)</th>
<th>( \theta_w ) (deg)</th>
<th>( \theta_c ) (deg)</th>
<th>( \Delta = \theta_w - \theta_c ) (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>8.0</td>
<td>7.50</td>
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</tr>
<tr>
<td>20</td>
<td>15.5</td>
<td>14.90</td>
<td>0.60</td>
</tr>
<tr>
<td>30</td>
<td>22.5</td>
<td>22.08</td>
<td>0.42</td>
</tr>
<tr>
<td>40</td>
<td>29.0</td>
<td>28.90</td>
<td>0.10</td>
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<tr>
<td>50</td>
<td>35.0</td>
<td>35.17</td>
<td>-0.17</td>
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<tr>
<td>60</td>
<td>40.5</td>
<td>40.63</td>
<td>-0.13</td>
</tr>
<tr>
<td>70</td>
<td>45.5</td>
<td>44.95</td>
<td>0.55</td>
</tr>
<tr>
<td>80</td>
<td>50.0</td>
<td>47.77</td>
<td>2.23</td>
</tr>
</tbody>
</table>
Imposing Patterns on Observations
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.
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.”
“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.”
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:

\[ F_{\text{grav}} = \frac{Gm_1m_2}{r^2} \]
If the theory fits...

Newton’s Rules for the Study of Natural Philosophy

- **Rule 1 – Simplicity** (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)

- **Rule 2 – Uniformity** (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.”
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.)
How do we introduce students to scientific uncertainty?
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.
An exercise

Circumference (cm)

Diameter (cm)

Circumference/Diameter

Diameter (cm)
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.
Accuracy, Precision, and Systematic Error

The Density of “21.5 ml” Water

Thursday, June 23, 2011
Data in Context: IPS

The Law of Conservation of Mass

-4.0%  -2.0%  0%  2.0%

Reactant Mass (g)

Number of Observations

-4.0%  -2.0%  0%  0.0%  0.4%  -0.4%  -0.8%  -1.2%  -1.6%  <-1.6%

Average Mass Change
This Year’s Data
Historical Data

The Law of Conservation of Mass

Thursday, June 23, 2011
Data in Context: Chemistry

Chemical Reactions and Mass

Mass Change

-20% 0% 20% 40% 60% 80%

Synthesis Single Displacement Precipitation Acid-Base Decomposition Calcination
Factors Affecting the Speed of Sound

Speed of Sound (m/s) vs Temperature (degrees C)

- Air
- Carbon Dioxide

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Data in Context: Biology

The Pasteur Effect

Aerated Yeast
Non-aerated Yeast

Time (min)
Normalized CO2 Production

Thursday, June 23, 2011
Beginning of the year survey:
The scientific method eliminates all uncertainty.

**Seventh Grade**
- True: 36%
- False: 64%

**Twelfth Grade**
- True: 8%
- False: 92%
“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.”
“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.”
References


• Ptolemy’s refraction data are from M. R. Cohen and I.E. Drabkin, A Source Book in Greek Science, Harvard University Press, 1948.


• Student Photos: Mike Pojman

• Campus Photo: Andrew Katz