HISTORY

1865 Maxwell equations
1879 Stefan radiation law
1879 Hall effect
1893 Wien radiation law
1885 Balmer series
1887 Michelson Morley experiment
1887 electromagnetic waves (Hertz)
1896 Radioactive decay (Becquerel)
1897 Thomson e/m
1897 Zeeman
1900 Planck radiation law
1900 photoelectric effect (Lenard, Millikan)
1905 Einstein quantization of light
1905 Einstein special relativity
1905 Einstein $E = mc^2$
1909 Millikan oil drop
1911 nuclear atom (Rutherford)
1913 Bohr mode
1914 Franck-Hertz
1923 Compton effect
1924 deBroglie hypothesis
1925 electron diffraction (Davisson-Germer)
1926 Schroedinger, Heisenberg

theory

expt in 2150

expt not in 2150
SCOPE OF THIS COURSE

• Experimental introduction to modern physics!
• “Modern” in this case means roughly the 20th Century
• Your goals:
  • take data effectively
  • keep a lab notebook
  • develop your understanding of how to do uncertainty analysis
  • present your results in written and graphic form
COURSE STAFF & WEBSITE

• Instructor
  • Professor Noel Clark
  • Course web site: www.colorado.edu/physics/phys2150

• Teaching Assistants
  • Junxiong Tang : Junxiong.Tang@colorado.edu
  • Zachary Snyder : Zachary.Snyder@colorado.edu

• Lab coordinators
  • Michael Schefferstein
    • Office: Duane G2B87
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SUPPLIES

- Syllabus (handout; on WWW)
- Lab manuals for each experiment (handout)
- Lab notebook (1 per student supplied)
- Error analysis pamphlet (handout)
- Radioactive material handling training
- Textbook: Taylor, “An Introduction to Error Analysis” (required)
- Clicker (available at University Book Store) (required)
REQUIREMENTS

- **PRE/CO-REQUISITES**
  - Have completed PHYS 1140
  - Are taking / have taken PHYS 2170 or 2130
  - Familiarity with numerical calculation program (Mathcad, etc.)

- **Taylor, Chapters 1-4**
  - Standard deviation
  - Standard deviation of the mean
  - Propagation of uncertainty
COURSE SCHEDULE: LECTURES

- Lectures are Tuesdays, 4:00-4:50

- PLEASE READ THE APPROPRIATE CHAPTERS IN TAYLOR BEFORE EACH LECTURE!

- Lecture 1 (January 23):
  - Review of syllabus, Error introduction

- Lecture 2 (January 30): Taylor Chapter 5
  - Uncertainty in Scientific Measurements, Random and Systematic Uncertainty, Gaussian Distributions, Mean, Standard deviation
COURSE SCHEDULE:
LECTURES / HOMEWORK

• Lecture 3: Taylor Ch. 6, 7
  • Rejection of data, Weighted averages

• Lecture 4: Taylor Ch. 8
  • Least squares analysis

• Lecture 5: Taylor Ch. 9, 11
  • Correlation analysis, Poisson statistics

• Homework: One assignment, worth one lab
  (assignment announced in class)
COURSE SCHEDULE: LABS

- **Signup:**
  - Sign up for experiments on the pages in the lab.
  - Sign up one lab in advance; don’t sign up for the whole semester at once.

- **You must do at least 6 labs**

- **Lab partners:**
  - You can work with a partner.
  - You and your partner must do separate write-ups.

- **Labs take 2 lab sessions**
LAB RULES AND PROCEDURE

• You will be issued a lab notebook.

• A lab diary and data must be recorded in your notebook.

• Do not erase. Correct mistakes by crossing out items, leaving them legible.

• Do not remove pages.
LAB SAFETY

• Some experiments use radioactive materials. You must complete the on-line radioactive handling course.

• The biggest hazards in the lab are high voltage (enough current capacity for an unpleasant shock!) and trips/falls. Never touch energized electrical components, and always look out where you are going!

• Treat the equipment with care
GRADING

- **Grades** will be based on the lab reports and the homework assignment.

- Labs take 2 lab periods
- Turn in the lab report the Friday of the week after the second lab session.
- Exceptions are Millikan and and Compton, which get an extra writeup week.

- Penalty for late reports
YOUR LAB REPORT

- Include any computer-generated work (Mathcad output, etc.) in your report.
- Number and date all pages in your report.
- Refer explicitly in the text to tables, calculations, graphs.
- Be professional and neat!
- Goal of report is to inform an educated reader, not as a record of your work.
YOUR LAB REPORT: FORMAT

- Experiment title
- **Objective:** Several sentence description of scientific goal (not “to learn about....”)
- **Idea:** Paragraph or two giving the basic ideas around how the experiment works and physics to be tested.
- **Apparatus:** Explanation of equipment. Draw carefully labeled diagrams including model numbers and any changeable connections! You can use scanned images.
YOUR LAB REPORT: FORMAT

- **Procedure:**
  - First person summary of process, including unexpected occurrences. What did YOU do?
  - Discuss problems and how they were resolved.

- **Data Analysis and Results:**
  - In the report inputs to all calculations must be written down explicitly.
**DATA FORMAT**

- **STATE FORMAL RESULT** ([SFR # in writeup])
  - State each result as an equation
  - Uncertainty rounded to 1 significant figure
  - Value rounded to uncertainty
  - Same power of 10 for value and uncertainty
  - Units expressed
  - **e.g.** - measured speed \( c = (3.44 \pm 0.06) \cdot 10^8 \text{ m/s} \)

<table>
<thead>
<tr>
<th>OK</th>
<th>NOT SO GOOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.41 ± 0.07</td>
<td>1.408 ± 0.07</td>
</tr>
<tr>
<td>6.7 ± 1.3</td>
<td>6.74 ± 1</td>
</tr>
<tr>
<td>0.1006 ± 0.002</td>
<td>0.1006 ± 0.004</td>
</tr>
</tbody>
</table>
DATA FORMAT

• **PLOTS**
  - *Data plotted as points, theory as lines*
  - *X,Y axes labeled with what is being plotted, with appropriate units*
  - *Caption, explaining what is important about the plot*
  - *Independent variable on the horizontal axis*
DATA FORMAT

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• PLOTS
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  - Caption, explaining what is important about the plot
  - Independent variable on the horizontal axis

• UNITS
  - Units of all quantities used on a page immediately evident on that page
  - Only one set of units in use at any given place in a report (e.g., lengths in meters)
YOUR LAB REPORT: FORMAT

- **Conclusions**
  - Short discussion summarizing (restating) results.
  - Compare results to accepted value: what is level of agreement based on your error estimate?
  - Further comment on uncertainties: explain basis of assigning them, possible hidden errors, etc.
  - Stick to scientific conclusions! No opinions, no personal comments.
GRADING CODES

- **RO**  
  Round off appropriately

- **1SF**  
  Express uncertainty with one significant figure

- **SPOT**  
  Same power of ten for value and uncertainty

- **SFR**  
  State final result in standard form:  \( x = (\text{val.} \pm \text{unc.}) \text{ UNITS} \)

- **AXL**  
  Label axes

- **(0,0)**  
  Include origin in plot

- **CAP**  
  No plot caption

- **LABEL**  
  No axis label

- **PDAP**  
  Plot data as points

- **UNITS**  
  Express units

- **SP**  
  Spelling problem
UNCERTAINTY, DISCREPANCY, & ERROR

- **“Uncertainty”**: A remnant lack of knowledge at the end of an experiment, appearing as a result of the fact that repeated measurements of a physical quantity always give different results under conditions where the same result is expected. Uncertainties are usually evaluated using statistical analysis and expressed as some range of possible values about a mean value. A result is meaningless without expressing its uncertainty.

- **“Discrepancy”**: The difference between your measured value(s) and the value(s) of the same physical quantity obtained in or calculated from other experiments or predicted by some theory.

- **“Error”**: Effects which systematically change measured values resulting from an experiment in a way that is not included in the analysis producing the design of the experiment, or arise from changes of conditions unbeknownst to the experimenter are said to introduce “systematic error”.
IN A SUM – Suppose a and b are some measured quantities. Measurement processes for determining a and b give well-defined averages and uncertainties \( <a> \pm \delta a \) and \( <b> \pm \delta b \). If we repeat the measurement process for a one more time we get \( a_i \), the “i th” measurement of \( a \), and we can define the fluctuation \( \delta a_i \) as \( \delta a_i = a_i - <a> \). Similarly for the j th measurement of b:

\[
a_i = <a> + \delta a_i \quad \quad \quad \quad b_j = <b> + \delta b_j
\]

where, by definition \( <\delta a_i> = <\delta b_j> = 0 \). If the fluctuations in a and b are independent, then the average of the product of the fluctuations is zero: \( <\delta a_i \delta b_j> = 0 \) (definition of independence). The quantities \( \sqrt{<\delta a_i^2>} \) and \( \sqrt{<\delta b_j^2>} \), always positive, are a measure of how big the fluctuations in a and b are in a single measurement.

Now we calculate the fluctuations in the sum \( c = a + b \). Treating fluctuations like differentials, we have

\[
<c> = <(a + b)> = <a> + <b>, \quad \text{and} \quad \delta c = \delta a_i + \delta b_j.
\]

\( <\delta c> = <(\delta a_i + \delta b_j)> = 0 \), so the average of \( \delta c \) doesn’t reveal anything about the magnitude of the \( \delta c \)'s. To probe this we calculate \( <\delta c_i^2> \):

\[
<\delta c_i^2> = <\delta a_i^2> + 2<\delta a_i \delta b_j> + <\delta b_j^2> = <\delta a_i^2> + <\delta b_j^2>.
\]

Since the cross term \( <\delta a_i \delta b_j> = 0 \) independent uncertainties in a sum add in quadrature:

\[
\delta c = \sqrt{<\delta c_i^2>} = \sqrt{(<\delta a_i^2> + <\delta b_j^2>)}
\]
WHY INDEPENDENT UNCERTAINTIES ADD IN QUADRATURE

**MULTIPLE INDEPENDENT MEASUREMENTS OF THE SAME QUANTITY** – Let \( c = (a_1 + a_2 + \ldots + a_N)/N \), where \( a_i \) are independent measurements of \( a \). Then \( c = \langle a \rangle \) and \( <\delta c^2> = [<\delta a_1^2> + <\delta a_2^2> + \ldots + <\delta a_N^2>]/N^2 = <\delta a^2>/N \), where all of the cross terms \( <\delta a_i \delta a_j> = 0 \). Thus, after averaging \( N \) independent measurements of \( a \), we have:

\[
a = \langle a \rangle, \quad \delta a = \delta \langle a \rangle = \delta a_i/\sqrt{N}, \quad \text{where } \delta a_i \text{ is the uncertainty for a single measurement}
\]
**WHY INDEPENDENT UNCERTAINTIES ADD IN QUADRATURE**

**IN A PRODUCT** – Let \( c = ab \). Then, using the chain rule \( dc = a \, db + b \, da \) or \( dc/c = da/a + db/b \)

\[
\frac{\delta c_i}{<c>} = \frac{\delta a_i}{<a>} + \frac{\delta b_i}{<b>}
\]

and

\[
(\frac{\delta c_i}{<c>})^2 = (\frac{\delta a_i}{<a>})^2 + (\frac{\delta b_i}{<b>})^2 + 2\frac{\delta a_i \delta b_i}{<a><b>},
\]

or

\[
\langle(\frac{\delta c}{<c>})^2\rangle = \langle(\frac{\delta a}{<a>})^2\rangle + \langle(\frac{\delta b}{<b>})^2\rangle = (\frac{\delta a}{<a>})^2 + (\frac{\delta b}{<b>})^2,
\]

so independent *fractional* uncertainties in a product add in quadrature:

\[
\frac{\delta c}{<c>} = \sqrt{\langle(\frac{\delta c_i}{<c>})^2\rangle} = \sqrt{(\frac{\delta a}{<a>})^2 + (\frac{\delta b}{<b>})^2}
\]

**IN THE GENERAL CASE** – Suppose \( c = f(a,b) \). Then

\[
\frac{\delta c_i}{a} = [\partial f/\partial a]\delta a_i + [\partial f/\partial b]\delta b_i
\]

and

\[
\langle\frac{\delta c_i^2}{a}\rangle = [\partial f/\partial a]^2\langle\delta a_i^2\rangle + [\partial f/\partial b]^2\langle\delta b_i^2\rangle
\]

so

\[
\frac{\delta c}{a} = \sqrt{\langle\frac{\delta c_i^2}{a}\rangle} = \sqrt{([\partial f(\langle a>,\langle b\rangle)/\partial a]^2\langle\delta a_i^2\rangle + [\partial f(\langle a>,\langle b\rangle)/\partial b]^2\langle\delta b_i^2\rangle)}
\]