Please pick up handouts from desk by door
Advanced Physics Lab

Introduction
PHY 327/424

• Welcome, Goals, People, Safety   9:10
• How to succeed in the APL      10:10
• Analysis and Uncertainty    11:10

These slides will be available online later today.
Welcome to the Advanced Physics Lab!

• Physics is the science that tries to describe, understand, and predict the behaviour of physical systems.

• Our goal is to help you learn the methods and understand the myriad challenges of making careful observations and accurate measurement of such systems, judging their consistency with theoretical models, and communicating this work.

• Doing the right thing more than getting the “right” answer. A “perfect experiment” is an oxymoron.

• Not showing up (enough) is the number one reason for a student not doing well in this course.
What is the Point of the Advanced Lab?

To help you learn all physics not taught in other courses.
What is learned in the Advanced Lab?

- **Instrumentation and methods**
  - Oscilloscopes, electronic meters, interferometers, lasers, lock-ins, vacuum, high voltages, cryogenics, spectrometers, X-rays, ...

- **Physics**
  - Classical, Quantum, Mechanics, Optics, Electromagnetism, Nonlinear, Nuclear, Particle, Condensed matter, biophysics, ...

- **Modelling**

- **Problem solving**

- **Analysis**
  - Nonlinear fitting with x & y error bars, uncertainty, interpretation, ...

- **Breadth & Design**
  - work on own (mostly)
  - design, decide, measure, analyse, communicate, ...

- **Communication**
  - oral, written
  - informal, formal
  - ...

- That science is messy

- ...

- That science is messy
What is learned in the Advanced Lab?

• Impossible to teach every physics topic or experimental method or other skills that you might need in your career

• We want you to develop your capacity to cope with new situations and learn new skills and knowledge.
How does the course work?

• **Read the Course Outline!**

• If you don’t read and understand the outline, you will likely do less well.

• **Ignorance is no excuse.**
  
  – Information often posted outside MP251, but don’t assume we’ll remind you about deadlines; they are in the outline and online.

  – If you don’t understand something – ask.
Grading Scheme
(PHY424)

- Data Analysis Project 4%
- 3 experiments @ 20% each 60%
- Formal Report and Peer Review 18%
- Oral exam 18%
Grading Scheme (PHY327)

• Data Analysis Project 4%
• 3 experiments @ 20% each 57%
• Design Reflection 3%
• Formal Report and Peer Review 18%
• Oral exam 18%
Dates and Deadlines

• In outline and at http://www.physics.utoronto.ca/apl/dates.htm
  o Experiment Preference Sheets due 4pm today
  o Start experiments in next lab period
  o Data analysis assignment due 23 September.
  o ...

• Let Coordinator know immediately if you notice any issues with the dates.

• Late penalties will be applied unless arrangements made in advance, or you are ill or have other valid excuse.
  – Contact relevant professor ASAP.

• Shelves and slots in MP251 may be used to hand in and return assignments, lab books, formals, ....
Preference Sheet

Tells us
- who you are
  - name you would like used (e.g. on whiteboard)
- how to contact you
- when you will be in the lab
- which experiments you would like to do
  - Experiments must be with different profs
  - You can always later ask for different experiment

Due by 4pm today (or hand in this morning)
Whiteboard in MP251
Attendance Sheet

Complete top and place in red binder in MP251, and sign in whenever in the lab.

By far our best predictor of student success in the Advanced Lab is whether we are seeing you regularly.

• You can skip lectures and still do well in a lecture course.
• You can pull an all-nighter to finish a problem set, but not an experiment.
• You cannot skip lab periods and do well in the Advanced Lab course. Experiments take time!
People

http://www.physics.utoronto.ca/~phy326/people.htm
IF YOU NEED HELP

• **Look** for (in order) Demo, Professor, Technologist.

• Profs and Demos are not around the whole lab period, but if you can’t find someone, **call** them.

• **Ask** Lab Coordinator.

• Outside regular lab periods, you can still call, but we are less likely to be available.
BUT ...

• No one in the lab understands all the experiments.

• If you ask a Professor or Demonstrator a question, the most common answer will be something like
  – “I don’t know, let’s sit down and see if we can figure it out.”
Questions?

• We’ll talk more about how to succeed in the Advanced Lab in hours 2 & 3.
• But now need to talk about academic integrity and safety.
Academic Integrity

Office of Academic Integrity: [http://www.artsci.utoronto.ca/osai](http://www.artsci.utoronto.ca/osai)

**Honesty, trust, fairness, respect, and responsibility**

- Ignorance is no excuse.
  - All students are expected to be familiar with the University's rules

- The primary product of academia is knowledge, so plagiarism and lying are cardinal sins.

- Always fully attribute and acknowledge!
  - don’t forget to acknowledge help in notebook
    - TAs, Profs, Techs, other students. ...

- Read guidelines, talk to Coordinator if unsure.
Plagiarism in Writing

• Never use sources without attribution.
  – e.g. Improperly copying just one sentence into your Formal Report is (in principle) sufficient for you to face serious sanctions from the Office of the Dean.

• It is better to lose a few marks because of poor writing instead of plagiarising and risking severe punishment.

• Students are caught and punished for plagiarising in the Advanced Lab.
Do not plagiarise Experiment Manuals for Formal Report

- Do not copy text except as properly attributed quotations!
- Attribute any figures used!!
- Do not plagiaphrase!!!
  - Reordering phrases, switching a few words, or using synonyms is not sufficient.
  - When paraphrasing, acknowledge the source somehow in the sentence/paragraph.
Questions?
Safety

• Everyone's responsibility. Staff do their utmost to ensure a safe learning environment, but in the end it is your skin (and your colleague’s).

• Always assess, consider, and mitigate any potential risks.

• Physics Health and Safety website

• All safety related incidents, including close calls, must be reported to lab staff.
Hazards

- compressed gases
- cutting edges
- cryogenic fluids
- dust
- fire
- flammable liquids
- heat
- heavy metals
- heavy objects
- high voltage
- intense sound
- lasers
- liquid oxygen
- low voltage
- magnetic fields
- radioactivity
- slip and trip
- toxic chemicals
- ultraviolet light
- vacuum
- x-rays
- ...

...
Safety Equipment

• You must use safety equipment provided
  – laser glasses, safety goggles, face-shields
  – gloves, ear-protectors, dust masks
  – ...

• Sandals are not safe and are not allowed.

• If you think you are missing safety equipment, ask any of the lab staff.
Fire

- Immediately notify lab staff if you smell any burning odour or see smoke.
- In case of fire: leave room, close door, pull alarm, exit building.
- If the fire alarm sounds, you must immediately exit the building. Do not use the elevator.
  - Notify the Lab Coordinator at the beginning of the course if you have mobility issues that might prevent you from using the stairs.
  - DO NOT RE-ENTER until authorized.
Ionizing Radiation

- Any student using an X-ray machine must wear a radiation dosimeter available from Technologist in MP 234.
- Radioactive sources must be signed out from the Technologist.
- Radioactive sources must never be left unsupervised, and must be returned whenever you leave the lab.
Emergencies

For immediate medical, fire, or police response,

CALL 911,

then call Campus Police at 416-978-2222.

If in doubt, call.

• Note, from phone in MP251 (or any university phone) call 9-911, then 82222
  – This is McLennan Physics, North wing, 60 St. George Street, room numbers on doors.
Final safety comments

• Most common unexpected risk is slipping in a puddle from leak or spill.
  – usually water, sometimes oil or particulates

• Don’t leave a mess!

• Food and drink are not allowed in the laboratory.
  – May eat or drink in MP251, but clean up.

• No question about safety is silly! Ask if you are unsure about anything.
Questions

? 

Don’t forget to take handouts.
The Way of the Physicist

Physicists

• construct mathematical model of a physical system
• solve the model analytically or computationally
• measure the system
• compare measurements with expectations
• communicate results with others
• improve model, calculation, experiment; iterate

Lecture Courses

I’ll be honest: we physicists talk a big game about the Theory of Everything, but the truth is, we don’t really understand why ice skates work, how sand flows, or where the static charge comes from when you rub your hair with a balloon.
Reminder: The goal of the lab is to improve your ability to measure and model physical systems and to communicate that knowledge.

What matters is trying to do the best job possible under the circumstances, while understanding and documenting what you are doing.
Experiments are tough

• What was the 1\textsuperscript{st} fundamental constant measured in a lab?
• What is the worst measured fundamental constant?

Newton’s Gravitational Constant: $G_N$

$\chi^2/df$ since

1798 is 138 (cdf=0)
1992 is 293 (cdf=0)
1995 is 13 (cdf=10^{-26})
(Un)Skills

Unskills

• Fear
  – of getting it wrong
  – of equipment

• Frustration
  – Not getting it right
  the first (or second
  or ...) time

Convert fear to mindfulness

Skills

• Playing
  – with equipment

• Persistence
  – not giving up

• Problem solving

• Judgment
  – are you finished?

• Focus
What is the Point?

• What is my goal?
• What am I trying to accomplish
  – in this course?
  – in this experiment?
  – today?
  – by making this measurement?
  – by doing this instead of that?
Idealized Experiment Progress

3 weeks to complete each experiment.

- **Week 1**: Become familiar with physics and apparatus, make plenty of notes and sketches, and attempt some preliminary measurements.

- **Week 2**: Complete at least one data-taking run and gone through all the analysis steps at least once.

- **Week 3**: Have some good data with well-understood uncertainties, and most analysis and conclusions well documented.
How science is done

As proposed

Actual (successful) research

As described in published journal article
A Typical Experiment Rubric

- Attendance (~2% per meeting with prof) 10%
- Effort (~6 productive hours/week in lab) 20%
- Experimental skill 20%
  ~ Achieve basic goals
  ~ Problem solving & making experiment work
  ~ Data quantity/quality
- Analysis of data/uncertainty 9%
- Understanding of physics and methods 6%
  ~ based on interview, notebook, and in-lab discussions
- Progress check* 5%
- Notebook quality* 14%
  ~ Page numbers, dates, times, diagrams/sketches, settings
  ~ Readability (legibility, organization, cross-references, ...)
  ~ Completeness
- Final summary/abstract* 6%
- Interview clarity* 3%

*At least 25% communications (& note that you can’t get credit for good work that we don’t know about or can’t understand.)
“Remember kids, the only difference between screwing around and science, is writing it down.”

Adam Savage, Mythbusters, Episode 190 “Titanic Survival”, Discovery Channel, 7 October 2012.
How a Prof reads a lab notebook

• We don’t read every word.
  – But we will be unhappy if we look for some information and cannot find it.
  – Completeness first, legibility second

• We start with the Summary/Abstract
  – Your chance to guide us.
  – What is the point?
  – What was accomplished?
  – Where to find stuff?

• We love forward/backward cross-references.

• Can’t get good marks for work that we don’t know about or can’t understand.
You need two lab notebooks

• You won’t get first notebook back before second experiment starts.

• May reuse lab-books from previous courses
  – number all pages from beginning of notebook, not beginning of experiment.
  – date at top of each page; note time frequently.

• Notebooks are journals, not formal reports!

• Notebooks are journals!!
  – record what happens when it happens, not later
  – We don’t want a beautiful fiction.
    • Unlike a formal report or scientific paper where the messy details and missteps may be omitted.
Photos document, diagrams model

• Write down all settings
  – often unreadable in photo.
  – makes you think about why they exist.

Note: In interviews and oral exams we may ask what a piece of equipment does and how to use it, and sometimes how it works.
Questions?
How get started

1) Read the experiment write-up.
   – But don’t trust it to be always accurate or up-to-date.

2) Check for safety warnings and issues.

3) Identify equipment
   – sketch apparatus and connections
   – note knobs and settings

4) Play with it.
   – “When I do this, that happens.”
   – Try to understand what it does, i.e. model its function.

5) If necessary, check the instrument manual
   – We have manuals for most(?) instruments.

6) If needed, repeat (4).

7) Ask TA, Prof, or another student for help
Measurement Models are as Important as Physics Models
e.g. ESR (Electron Magnetic Moment)

Physics Model

- QED: $\mu_e (1 + a_e) \frac{e}{m} \hat{S}$

Fourteen thousand Feynman diagrams later

- $a_e \times 10^{12} = 1159652181.643$
  - $\pm 0.025$ (8th order QED)
  - $\pm 0.023$ (10th order QED)
- $\pm 0.016$ (weak/hadronic)
- $\pm 0.763$ ($\alpha_{Rb10}$)

Measurement Model

- dipole in uniform magnetic field
  - DC electromagnet
  - AC coils
  - gaussmeter
- microwaves
  - Gunn diode
  - Resonant cavity
  - waveguides
  - magic T
  - modes
  - absorption
- electrical measurement
  - oscilloscope, multimeter
- electrons in matter
  - how free are they?
- experimenter makes many decisions
- ...
Problem solving

1) Restart
   – Turn equipment off and on, restart program, reboot computer, retake data, ...

2) Read the manual.

3) Model, then compare to reality.

4) Calibrate
   – Measure something you know.

5) Break down problem into components
   – Test each component separately.
     ○ But life is not always linear: sometimes components work fine alone, but not together.

6) Iterate
Try to be efficient*

Where should you take more data?

* But “if you are not wasting some time, you are wasting time”; “the perfect is the enemy of the good”
Where should you spend your time here?
Flag Anomalies

That’s weird, ...

• If there is some aspect of your analysis (or experiment) that doesn’t make sense, say so in your lab notebook!

• Even if you don’t have time or the tools to investigate further, you want to be the one that points out issues, not the professor.
APL Mistakes

Experiments
• Not showing up
• Not talking regularly to Profs & Demos
• Trying to understand everything before taking data.
• Taking data without understanding anything.
• Not analyzing data as you go.
  – You can’t understand your data without taking some data
  – Better to have less data that is well understood rather than lots of data poorly analyzed.

Formal Report
• Skipping peer review
  – “only worth 1.1% of final grade”
  – but also typically lose several % because of poor report.
You Can Do It!

• You have all completed at least 2 years of university level physics.

• All these labs have something interesting that you can figure out and learn from.

• Try to have fun!

• Often things go wrong or something breaks or changes
  – That is part of experimental physics (and scientific research in general).
  – Just document EVERYTHING in your notebook, try your best to fix things, and seek help when appropriate.

• If you do these things, show up regularly and put in your best effort, you will be well on your way towards a good grade in this course!
Questions
?

DATA: BY THE NUMBERS

NUMBER OF YEARS TO
GET DATA: 3

YES! FINALLY!

NUMBER OF YEARS TO
INTERPRET DATA: 2

what does it all mean??

NUMBER OF YEARS TO
WRITE ABOUT DATA: 1.5

blah blah blah blah...

NUMBER OF SLIDES TO
PRESENT DATA: 1

RESULTS
that's it?
Data and Uncertainty

• Natural science is fundamentally inductive, not deductive.

• Data is used to modify our beliefs in
  – whether hypotheses are true
  – the likely values of parameters in our models

• Uncertainties parameterize the likelihood that two measurements will agree.
  – not the probability distribution for the true value

• Uncertainties are defined by convention.
  – If everyone uses the same reasonable convention, we can compare results.
“$x \pm \sigma$” means

1. if other measurements of the same parameter are made, “$x_i \pm \sigma_i$”, we expect

$$|x - x_i| < \sqrt{\sigma^2 + \sigma_i^2}$$

2. 68.3% of the time.
Normal (Gaussian) Distributions

\[ P(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \]

Mean \( \mu \), RMS width \( \sigma \)

• Limit of Binominal distribution for many trials with mean not near zero.

• The Central Limit Theorem says (almost?) everything averages out to a Gaussian.

• Many resolution functions approximately Gaussian.
Normal Assumption

• Often works pretty well for “statistical uncertainties”, i.e. those uncertainties that automatically get smaller as you take more data.

  – e.g. $\sigma_{\text{stat}} = \frac{\sigma_{\text{STD}}}{\sqrt{N}}$

• But understanding the systematics is what takes forever … (literally)
Systematic Uncertainties

Correlated (rather than random) errors that are NOT simply reduced by taking more data. Due to inaccurate measurement model

- **Mis-calibration**, e.g. Thermocouple ref temp
- **Uncertain inputs**, e.g. COMP: Pure Pb?
- **Theory dependence**, e.g. Thick or thin LENS?
- **Instrumental**, e.g. ground loops
- **Backgrounds, noise, inefficiencies**, ...

Causes long uncertainty tails!

http://rsos.royalsocietypublishing.org/content/4/1/160600
Experimental Paranoia

Assume that the universe is conspiring to spoil your experiment.

e.g. Don’t assume equipment is calibrated, that it is the same as the last time you used it,* there are no typos, there is no noise, ...

* If you do make such assumptions, clearly state them in your notebook.
Analysing Data

e.g. for Data Analysis assignment
Fitting

“Fitting” data means adjusting the variable parameters in the physics (mathematical) model so that it best agrees with the data.

- A metric is used to measure agreement between the model and the data. A fit minimizes the value of the metric.
- Most common metric is $\chi^2$. 
Software

• Matlab, Octave, Sage...
• Maple, Mathematica, Reduce, ...
• Excel (for preliminary analysis)
• Faraday, DataStudio, Kaleidagraph, ...
• Python, C, C++, ...

We don’t care what you use, but we do care that you understand what you do.

But, if in doubt, use Python, since that is the language we support.
Weighted Least Squares

- Minimize

\[ \chi^2 = \sum_{i=1}^{n} \left( \frac{y_i - f(x_i; p)}{\sigma_i} \right)^2 \]

- Ordinary/linear least squares assumes equal uncertainties and hence minimizes

\[ \chi^2 = \frac{1}{\sigma^2} \sum_{i=1}^{n} (y_i - f(x_i; p))^2 \]

- Never, ever, use Ordinary Least Squares if the uncertainties are not equal!

- Fit should give best values for parameters, their uncertainties, and \( \chi^2 \) and CDF (cumulative distribution function) for the fit.
Python for the Advanced Lab

http://www.physics.utoronto.ca/~phy326/python/

• curve_fit_to_data.py
  – simple_curve_fit_to_data.py
  – extended_curve_fit_to_data.py

• odr_fit_to_data.py
  – for errors in x and y

• odr_fit_extended.py (new)
  – calibration or systematic errors
  – non-Gaussian uncertainties

• If you don’t base your analysis on these, please be sure you know what you are doing.
Example

http://www.physics.utoronto.ca/~phy326/python/curve_fit_to_data.py

Converged with ChiSq = 112.294154061, DOF = 96, CDF = 12.2457839215%
$\chi^2$ does not tell you everything

- $p\bar{p} \rightarrow \pi^+\pi^0\pi^-$ Charge Conjugation Test

\[ \chi^2 = 218.9 \text{ for } 200 \text{ dof} \]
\[ \chi^2 / \text{dof} = 1.09 \]
\(\chi^2/\text{dof}\) is insufficient

<table>
<thead>
<tr>
<th>(\chi^2/\text{DoF})</th>
<th>DoF</th>
<th>CDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.09</td>
<td>200</td>
<td>18%</td>
</tr>
<tr>
<td>1.09</td>
<td>800</td>
<td>4%</td>
</tr>
<tr>
<td>1.09</td>
<td>3200</td>
<td>0.02%</td>
</tr>
<tr>
<td>1.7</td>
<td>200</td>
<td>0.0000002%</td>
</tr>
<tr>
<td>1.7</td>
<td>20</td>
<td>3%</td>
</tr>
<tr>
<td>1.7</td>
<td>8</td>
<td>9%</td>
</tr>
</tbody>
</table>

\(\chi^2/\text{dof}\) near 1 does not always mean it is a good fit.

\(\chi^2/\text{dof}\) away from 1 does not always mean it is a bad fit.
$\chi^2$ does not tell you everything

- $p\bar{p} \to \pi^+\pi^0\pi^-$ Charge Conjugation Test

\[
\chi^2 / \text{dof} = 1.09, \quad \text{CDF} = 18% 
\]

\[
\frac{N(\pi^+)}{N(\pi^-)} = 1.0096 \pm 0.0032 
\]

CDF = 0.27%
Is this a good fit?

- i.e. Do (red) data and (yellow) model agree?

\[ \chi^2 = 218.9 \text{ for 200 dof} \]
\[ \chi^2 / \text{dof} = 1.09 \]
Is this a good fit?

Weighted least squares fit

\[ \chi^2 = 729 \text{ for 17 D.O.F.} \]

CDF = \(6 \times 10^{-142}\%\)
What about this data?

\[
\chi^2 = 15 \text{ for 17 D.O.F.} \\
CDF = 60\%
\]
How do you fit this data?
Orthogonal Distance Regression

• Good when both $\sigma_x$ and $\sigma_y$ are significant

• Minimizes orthogonal distances from data to curve:

$$\sum_{i=1}^{n} \left( \frac{\varepsilon_i}{dy^*} \right)^2 + \left( \frac{\delta_i}{dy^*} \right)^2$$
ODR Example
(parabola_xy_errors.txt)

ODR: $\chi^2/\text{df} = 0.96; \ CDF = 51\%$

LSq: $= 3.3; \ CDF = 0.0002\%$
Data analysis in the Advanced Lab

References


• Lectures on course website by Bailey, Krieger, Thywissen, Harrison
Data Analysis Assignment

• Required of all first-time APL students
• Ensures students have skills needed for APL data analysis.
  – nonlinear fitting
  – uncertainties in both $x$ and $y$
  – careful thought and communication about analysis and uncertainty.
Questions?
Reminders

• Return Preference Sheet by 4pm today.
  – Your experiment will be posted on course website by Monday noon.

• Read the course outline.
  – Talk to me if you have questions.

• Have Fun!

[Image: The Difference, https://xkcd.com/242/, by Randall Munroe (CC BY-NC 2.5), rearranged]