Spring 2024

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Methods of Experimental Physics
(Physics 3700)

Class Goals:

As incredible as it might sound physics is a science that is based on experiment. No matter how mathematically elegant or intuitively obvious a theory might be it lives or dies depending on experimental verification. Such comparison, however, is only valid when the uncertainties in the measurement are correctly estimated. It is therefore important that early in your scientific careers you get aquatinted with the experimental tools and procedures that are common in the laboratory environment. With this in mind the goal of this class is to introduce you to many of the methods of experimental physics that allow us to differentiate the crackpots from the geniuses! Even if you will not work in physics research related field in the future, you will find many applications in daily life!

This course stresses data analysis in a physics laboratory setting. We will start with some fundamental concepts from probability and statistics and build on them until we are doing very sophisticated things like non-linear least squares curve fitting and computer simulation of experiments. For more details on the subjects and experiments covered in the class see the course outline.

The use of computers is integrated throughout the course. Each student has access to a PC that can be login with your OSU credential. Throughout the course computers will be used in a variety of ways including control and simulation of experiments and writing programs and lab reports. Each PC has a graphing program LabPlot2, a free software that you can also download to your computer. This is the official plotting program and the use will be demonstrated in one of the lectures. For the first three labs, you can use Excel for the plotting. However, starting in Lab 4, LabPlot2 should be used.

Please communicate via e-mail rather than using Carmen. For homework questions, please e-mail Dr. Leonard, rleonard@physics.osu.edu.

Course Web Site: https://www.asc.ohio-state.edu/gan.1/teaching/spring24/3700.html

Coursework:

Lecture: Smith, Room 1009 Lab: SMITH 2064

Lectures:	Monday	10:20-11:15
Laboratory:	Mon, Tues, Thurs	1:00-5:00
Office Hour:	Thursday	11:30-12:30

This class contains both a lecture and laboratory component. The emphasis of the class is on lab work. However approximately an hour a week will be devoted to introducing and discussing the material necessary to perform the lab exercises. I expect students to have a physics background at the level of the Physics 1200 sequence and a calculus background at the level of familiarity with derivatives and integrals.

Grades:

Your course grade will be determined with the following weighting scheme:

Homework:	25%
Lab reports:	50%
Final Exam:	25%

There will be six homework sets and each set will be worth 4.17% of the course grade. The homework sets will be distributed about every two weeks. There will be seven labs and each lab report will be worth 7.14% of the course grade. The penalty for late homework and lab report is 5%/day. Please submit your lab report/homework to Carmen as a pdf file. The final exam, worth 25% of the course grade, will cover the material in lecture and homework.

Lectures:

The lecture notes are reasonably self-contained but they are not written in the form of a textbook. You need to attend the lecture to understand some of the rather complex ideas. You may not fully understand some of the complex ideas during a lecture but at least it will help you understand the idea when you review the notes and read the textbook. I will also emphasize during lecture what is important as you prepare for the final exam. **Students that attend the lectures perform much better in the final exam!**

Labs:

The labs apply some of the statistical data analysis techniques introduced in the lectures:

Lab 1 (Lec 1): demonstrate that the precision of a measurement increases with statistics.

Lab 2 (Lec 2): demonstrate the concept of binomial and Poisson statistics, including the calculation of the binomial uncertainty in the measurement of π.

Lab 3 (Lec 3): demonstrate the central limit theorem.

Lab 4 (Lec 4): demonstrate the propagation of errors.

Lab 5 (Lec 5): measure the energy spectra of three radiative material. Identify a total of five prominent peaks from the three spectra and plot the energy of the peak vs. voltage to find the relationship between the measured voltage and known energy. This is how you calibrate an apparatus.

Lab 6 (Lec 6-7): measure the energy resolution of the apparatus with various techniques, from the quick rudimentary technique to fitting each spectrum to get the width (resolution) of the distribution (apparatus). Simulate one of the observed spectra.

Lab 7 (Lec 7): measure the lifetime of Ba137. Perform both linear and exponential fits to the decay spectra. Simulate the radiative decay exponential distribution.

Each lab will have a set of questions and/or exercises. Your lab report should include answers to these questions/exercises. These lab exercises will vary in scope from simple tasks such as graphing data to complex tasks such as fitting your collected data to extract parameters of interest with the best precision. **Don't lose points for failing to answer questions!**

You should be able to complete the lab within the lab time. You are strongly encouraged to do the lab during the lab time so that you can show your result to the instructor as it became available to correct any problem. A few students would collect the data and then leave to analyze the data at home because they think they know what they are doing! These students often **loss** a lot of points for analyzing/plotting the data wrong. **Disclaimer**: the instructor might tell you that the plot looks OK during the lab time but it is your response to make sure the plot is correct when submitting the lab report since the instructor doesn't have time to inspect your plot with a fine comb.

<u>Homework:</u>

The homework is designed to reenforce some of the ideas covered in the lectures:

HW1 (Lec 1): basic concept of statistics and probability distribution.

HW2 (Lec 2-3): binomial and Poisson statistics.

HW3 (Lec 4): propagation of errors.

HW4 (Lec 5-6): maximum likelihood and least square fitting.

HW5 (Lec 6): more on least square fitting.

HW6 (Lec 6-8): more sophisticated fitting and calculation of upper limit.

Final Exam:

The final will cover the material presented in the lectures. How to prepare for the final exam? Practice the example problems in the lecture notes and homework. Make sure that you understand how to solve the problem (i.e. you can explain to others on how you solved the problem). Simply reviewing (looking at) the problems will not help if a problem in the final is not identical to that in the lecture note or homework.

Course Textbook:

The textbook for this course is:

An Introduction to Error Analysis, by John Taylor

This is a textbook that explains data and error analysis at a level suitable for this course. However, the ordering of the chapters in this book is not the same as the order that topics will be discussed in class. The lectures follow the sequence in the prior text, *Statistics*, by Barlow, which organizes the topics in a more logical manner. While this is an excellent text, it was not popular with students as they felt that it was not at the appropriate level for this class.

Physics 3700 Course Outline

Week 1-2 (Taylor: 1.1-1.4, 2.1-2.4, 4.1-4.3, 5.1-5.2 = 31 pages)

Introduction to the concepts of probability and statistics. Discrete and continuous probability distributions. Define some common terms such as mean, mode, median and variance. Discuss statistical and systematic errors in the context of modern physics experiments. Familiarization with laboratory equipment (computers and associated software). Some simple experiments with coins and dices. Introduction to the use of random numbers using the computer. Use the computer to plot, graph, and histogram data.

Week 3-4 (Taylor: 1.5-1.6, 3.1-3.2, 10.1-10.4 (pg. 234), 11.1-11.2 (pg. 252) = 18 pages)

Lecture on the binomial and Poisson probability distributions. Throw darts (both real and virtual) to estimate π. Compound experiment with dice to illustrate the binomial distribution. Experiment with cosmic rays to demonstrate Poisson distribution. More practice with computer programming and data analysis.

Week 5-6 (Taylor: 4.4-4.5, 5.3-5.4, 10.4 (pg. 234)-10.5, 11.2 (pg. 252)-11.3 = 19 pages)

Lecture on the normal (Gaussian) distribution. Discuss the relationship between the binomial, Poisson, and normal distributions. Introduce the central limit theorem. Perform experiment that generates a normal distribution. Generating the normal distribution using a computer.

Week 7 (Taylor: 2.5, 2.7-2.9, 3.3-3.11, 4.6 = 43 pages)

Lecture on propagation of errors in physics experiments. Demonstrate the propagation of errors in the resistor experiment.

Week 8 (Taylor: 2.6, 5.5-5.6, 7.1-7.3 = 18 pages)

Lecture on the determination of parameters from experimental data. Introduce the concept of Maximum Likelihood. Define weighted average.

Week 9 (Taylor: 5.7-5.8, 8.1-8.5, pg.108, 12.1-12.3 = 31 pages)

Lecture on advanced methods of determining parameters from experimental data. Introduce “least squares fitting” and the χ^2 test. Start to set up several nuclear physics experiments that will be used the rest of the course. These experiments will also familiarize the students with the concepts of computer controlled data acquisition.

Week 10 (Taylor: 12.4-12.5 = 7 pages)

Lecture on the techniques of hypothesis testing to compare the experimental data to theoretical expectations. Introduce parametric and non-parametric testing. Discussion of confidence levels using examples from several areas of physics. Determine the energy levels of Na^{22}, Co^{60} and Cs^{137}. Calibrate the electronics used in the nuclear physics experiments using a linear least squares fit.

Week 11 (Taylor: 6.1-6.2 = 5 pages)

Lecture on error on the mean. Advanced topics in least squares fitting. In the lab measure the gamma ray energy spectrum from the radioactive sources.

Week 12 (Taylor: 8.6, 11.4 = 7 pages)

Fit the measured energy spectrum to a “complicated” function (e.g. a Gaussian line shape + a linear background) using the techniques discussed in lecture.

Week 13-14

Set up and start to perform an experiment that illustrates the exponential probability distribution and allows the half-life of a radioactive isotope to be measured. Use Monte Carlo method to simulate the half-life experiment.

Summary of Laboratory Experiments

I Simple experiments with coins and dices

- Can you predict the outcome of a coin?
- Is your coin or die "loaded"?
- Generating a binomial probability distribution by throwing one or two dices

Monte Carlo method

- Writing programs
- Generating probability distributions
- Simulation of physics experiments

II Determining π by throwing darts and by computer simulation

Compound experiment with dices

- Generating a binomial probability distribution by throwing 12 dices

Generating a Poisson distribution using cosmic rays

III Generating a normal distribution in an experiment (Central Limit Theorem)

Generating the normal distribution using a computer

IV Demonstrate the propagation of errors by comparing the width (sigma) of a resistor pair with the prediction based on the individual width of the two resistors.

V Computer controlled data acquisition

Measurement of the energy levels of radioactive sources

Fitting the measured energy levels to calibration the electronics

VI Measurement of the gamma ray energy spectrum

Fitting the measured gamma ray energy spectrum to determine the energy resolution

VII Measurement of the half-life of a radioactive isotope

Simulate the half-life decay distribution using a Monte Carlo technique

GE Requirement: The data analyses above are designed to satisfy the GE Data Analysis requirement.

Academic Misconduct: Not to report academic misconduct is itself regarded as academic misconduct (AM). Everyone in the university community has a duty to report suspected AM.

Students with Disability: Please contact Prof. Gan at the start of the semester so that arrangements can be made to accommodate you. Students needing the services provided by the Office for Disability Services (ODS) will need to be certified by that office. The ODS is located in 150 Pomerene Hall, 1760 Neil Avenue; telephone 292-3307, TDD 292-0901; http://www.ods.ohio-state.edu/.

Faith-Related Absences: You may be absent from class for up to three days for reasons of faith, religious or spiritual belief system to participate in organized activities conducted under the auspices of a religious denomination or spiritual organization. Notifications for all specific dates that are being requested for religious accommodation must be made to your instructor in writing no later than the 14th day after the first day of the semester (Mon 1/22/24).

Acknowledgment: This material is adapted from the course developed by Prof. Richard Kass.