Syllabus for Principles of Experimental Research (ECE 446)

Prof: Lynford Goddard, lgoddard@illinois.edu, Micro and Nanotechnology Lab 2254
Office Hours: Thursdays 10-11A hybrid: MNTL 2254 and Zoom (contact instructor for link)

TA: Alex Littlefield, ajl8@illinois.edu
Office Hours: TBD
Lab Hours: Fri noon-6pm in ECEB 3077. The Wed 7:00-9:00pm portion of office hours can be held in ECEB 3077.

Course Webpage: https://canvas.illinois.edu/courses/61933

Lectures: MWF 11-11:50am hybrid: ECEB 2015 or Zoom (contact instructor for link).
Lab: F noon-2:50pm (section AB1) or F 3-5:50pm (AB2) in ECEB 3077 or asynch/remote (by arrangement)
Final Exam: Wednesday, Dec. 17th 8:00am-11:00am
Course Software: Available in ECEB 3077 and also the ECEB 3022 EWS lab

Units: 4 hours of graduate or undergraduate credit

Grading Policy:

Homework	15%
Labs	20%
Project: Proposal, Paper, and Poster	25%
Conference Talk	10%
In-class Quiz 1	8%
In-class Quiz 2	8%
Final	14%

About the Course: "Principles of Experimental Research" is an interdisciplinary course designed primarily for first year graduate students and advanced undergraduates in engineering and science. It has been approved as an ECE departmental laboratory elective and as a professional development course for the ECE M.Eng. degree. The prerequisite is ECE 313 or equivalent. It is recommended but not required that the student have knowledge of ECE 310, ECE 329, and MATH 415 or equivalent.

The course draws on laboratory problems in engineering and covers topics in: (1) design of experiment, (2) prevalent experimental techniques and instrumentation, (3) data collection, organization, and statistical analysis techniques, (4) oral and written presentation of scientific material, and (5) scientific computing languages and software. Open-ended labs and an independent project reinforce concepts discussed in class. Students will build and test: (1) a software-based lock-in amplifier in LabVIEW using a DAQ card, (2) a PID motor controller in LabVIEW using table-top instruments or a DAQ, (3) audio and optical heterodyne systems, and (4) an electrical time domain reflectometer. They will also carry out an experimental project of their own design that determines and models the main effects and their statistical significance in a multivariable experiment. Students will present scientific material in three common formats: at a poster session, at a conference talk, and in a journal paper. The main course objective is for students to develop the basic skills needed for pursuing a career or an advanced degree involving experimental research. The course topics include:

1. Course introduction and laboratory safety including how to define a safety plan (1 lecture)
    a. Integrated Safety and Management (define scope of work, identify hazards, select protective equipment, perform the work, and provide feedback on lessons learned)
2. Automated data collection in LabVIEW (3 lectures)
    a. Basic structures, the GUI, Controls and Indicators, Debugging, XY Graphs
    b. Using Pre-written VIs, Control loops, Send/Read on GPIB, Save XY to files, Acquiring signals with a DAQ card
    c. Signal processing, analysis, and display in LabVIEW, MathScript, Express VIs, Advanced data flow constructs, Instrument control
3. Gaining pre-experiment insight (1 lecture)
    a. Back of the envelope calculations
        i. Estimation for feasibility
        ii. Dimensional analysis and the Buckingham π theorem (Identifying the key dimensionless parameters from a list of variables)
4. Planning a research project (1.25 lecture)
    a. Performing literature searches; writing a good statement of work
        i. Common weaknesses of failed research proposals
    b. Project charts
        i. Penta chart (A single PowerPoint slide that describes a proposed research project and why the research should be conducted)
        ii. Gantt chart and critical path analysis (CPA)
    c. Documentation and technical reports
5. Design of experiments (DOE) (6 lectures)
    a. Selecting a design to meet the objectives of the experiment (1.5 lectures)
        i. Sampling (simple random sampling, stratified random sampling, block design, and matched pair)
        ii. Critical thinking, deductive and inductive logic, scientific method
        iii. Selecting a domain
    b. Full factorial designs
    c. Fractional factorial and Plackett-Burman designs
    d. Initial analysis of DOE data (0.5 lectures)
    e. Analysis of a full factorial experiment
    f. Analysis of a fractional factorial experiment
6. Preparation of results for publication (1 lecture)
    a. Abstracts, poster sessions, conference talks, journals, and patents
    b. Manuscript guidelines, style, editing, clarity versus conciseness
    c. Being a referee for an article and responding to referee remarks
7. Project evaluation (1 lecture)
    a. Earned Value Management
8. Data organization and statistical analysis techniques (13 lectures)
    a. Sources of error, confidence intervals, propagation of error, systematic and random components of uncertainty, and graphs/data representation (scatter-plot, box-plot, 2D intensity, histogram, normal probability)
    b. Linear regression without and with error in the x-coordinate; multivariate linear regression (0.5 lectures)
    c. Polynomial regression; robust linear fitting and estimation techniques for data with statistical outliers
    d. Hypothesis testing; tests of significance; student t-distribution, comparison to the null hypothesis (1.5 lectures)

    e. Type I/II errors and receiver operating characteristics (ROC)
    f. Analysis of variance (ANOVA) (1.5 lectures)
    g. Nonlinear curve fitting techniques
    h. Testing goodness of fit; cross validation
    i. Interpolation/extrapolation, numerical integration/differentiation, Runge-Kutta
    j. Noisy data, Averaging, Wiener filtering, and Savitzky-Golay smoothing
        i. Boxcar averagers
    k. Finding extrema and points of inflection in noisy data (0.5 lectures)
    l. Monte Carlo techniques
        i. Experimenting via simulation
        ii. Bootstrapping
    m. Principal component analysis
9. Experimental techniques and instrumentation (7.75 lectures)
    a. Null, differential, direct/indirect and lock-in measurements
        i. Wheatstone bridge (null)
        ii. Interferometers (null)
        iii. Oscilloscopes (differential)
        iv. Small signal modulation-response analysis (differential)
        v. Ground loops and returns
    b. Static and dynamic characteristics of instruments (0.75 lectures)
        i. Accuracy, precision, resolution, tolerance, sensitivity, span, linearity, dynamic range, drift of the zero offset and response slope, etc.
        ii. Zero, first, and second order instruments
    c. PID control systems
    d. Heterodyne detection
        i. Lock in amplifiers
        ii. Electrical spectrum analyzers
        iii. Laser linewidth
        iv. Laser Doppler vibrometers
    e. Self-calibration
    f. Pump-probe experiments (0.5 lectures)
    g. Electrical and optical time domain reflectometry (0.5 lectures)
    h. Temperature dependent studies (0.7 lectures)
        i. Exploration of physical phenomena
        ii. Arrhenius plots
    i. Wavelength modulation spectroscopy (0.7 lectures)
    j. Cavity ringdown spectroscopy (0.6 lectures)
10. Special topic or guest lectures (2 lectures)
    a. Prototyping
        i. Soldering, dimensioning of drawings, AutoCAD, choice of materials and tools
        ii. Working with the ECE professional machine shop, access to student shop
        iii. Working with the Illinois MakerLab, 3D printing
    b. Ethics in research
11. Reviews (2 lectures)
12. Class activity days – poster session and conference talk (2 lectures)
13. In-class quizzes (2 lectures)

Proficiency in multiple scientific computing languages and programs is a skill required of today's experimentalist. Some students already have significant experience either through formal classes or independent learning, while others are still learning. To address the differences in needs, this course will offer optional demo style discussions occasionally during the semester (during a few of the instructor's office hours) to discuss sample code in LabView, Origin, and Matlab, and to a lesser extent AutoCAD, Mathematica, and SAS JMP. In addition, the website will contain links to tutorials. Homework assignments, exams, and regular lectures will generally require basic knowledge of LabView, Origin, and Matlab. If there is sufficient interest, Python, C, and LaTeX can also be discussed during the optional sessions.

The class will have four open-ended labs, one independent experiment, two conference style presentations, some homework assignments, two in-class quizzes, and a final. There will be two special class days (poster session and conference talk) that span outside of normal class hours. We will schedule it in a way that students only need to attend part of these events. All assignments are due at 11 pm. Typically, homework assignments are due on Wednesdays and labs are due on Fridays. Two exceptions are that the main project proposal and the poster/abstract draft are due on a Monday. Some weeks do not have HW assignments and other weeks do not have lab assignments due. **All assignments should be submitted via gradescope by their due dates**.

The 3077 lab has basic equipment: DMMs, oscilloscopes, multifunction data acquisition cards, computers, etc. and will be available during hours described above for students to complete the labs and to develop their independent experiment. In 2021, we developed a hardware lab kit to enable students to complete the labs remotely (except for soldering).

Lab #0 is a short session (10-30 minutes) to learn how to solder. The first two real labs are in weeks 2-5. Students will write LabView software to control the output of lab instruments and collect data automatically. They will demo their experiment to the TA (10 minutes) and submit their code.

The main project is an individual lab experiment consisting of designing, planning, and performing a simple multivariable screening experiment. Each student will submit a research proposal consisting of a 150-word abstract in week 5 and a Penta chart, safety assessment, a Gantt chart with CPA and estimated cost, and a statement of work at the beginning of week 7. Students may request parts for their projects from the ECE shop. In week 9, each student will submit a draft of a two-page paper describing their experiment, analyzing the data and trends through graphs, and conforming to IEEE journal style guidelines. After receiving feedback, they will submit the final version in week 11.

The first conference style presentation, in week 12, will be a poster session (10:30a-12:30p in ECEB Atrium) where each student will present the results of their independent project. A 50-word abstract will be due in week 11 for inclusion in an abstract booklet. The poster session will be open to the public. Students and faculty from outside the course are encouraged to attend.

The third lab is in weeks 11-12. Students will build and characterize an electrical heterodyne circuit and will use a pre-built tabletop optical homodyne system to measure laser cavity length and vibrations in a mirror caused by sound waves. Students will write LabView code for automated data collection for both experiments.

The fourth lab is in weeks 14-15. Students will configure an experimental setup for performing electrical time domain reflectometry and determine the impedance and fault locations of various cables.

The second conference style presentation will be a 15 minute talk (12 minute presentation, 3 minute Q/A) during the last week of class, but scheduled between 10a-4p. Depending on enrollment, the class will be divided into one or more sessions and each student will present a summary of an experimental technique from the literature on a topic outside those listed in the syllabus. A 150-word abstract will also be submitted and will be printed in an abstract booklet. The conference talks will also be open to the public.

The four lab exercises and the main project are open-ended. Extra credit (to bring the lab score or project score up to a maximum of 100%) requires demonstration of additional functionality or performance of additional analysis beyond what is described in the general assignment. For example, the lock-in lab can be expanded to demonstrate derivative spectroscopy (harmonic detection); the PID motor lab can be expanded to perform PID temperature control; the electrical time domain reflectometer can be expanded to perform cavity ringdown analysis of the loss in a cable; the heterodyne lab can be expanded to build a laser Doppler vibrometer or to perform laser linewidth measurements; the main project can have a response surface experiment in addition to the 3-variable full factorial experiment or it can have a 4- or 5-variable fractional factorial experiment.

In this class, students are encouraged to perform experiments or present topics related to their graduate research or senior thesis projects with the one caveat that the work must be new, i.e., not simply a derivative of past work or something they were assigned or planning to do anyway.

Lecture notes will be available for download. The required course textbooks are:

1. Principles of Experimental Research Course Packet, F&S Printing Department, 2021.
2. Data Reduction and Error Analysis for the Physical Sciences by Philip R. Bevington and D. Keith Robinson (publisher: McGraw-Hill), 3rd edition, 2003.
3. NIST/SEMATECH e-Handbook of Statistical Methods, available free of charge online at: http://www.itl.nist.gov/div898/handbook/

Optional, but highly recommended textbooks (to be available on reserve in Grainger library) are:

4. Statistical Quality Design and Control by Richard E. DeVor, Tsong-how Chang, and John W. Sutherland, (publisher: Prentice Hall), 2nd edition, 2007.
5. Numerical Recipes: The Art of Scientific Computing by William H. Press, Saul A. Teukolsky, William T. Vetterling, and Brian P. Flannery, (publisher: Cambridge University Press), 3rd edition, 2007.

Additional references:

6. Introduction to Engineering Experimentation by Anthony J. Wheeler and Ahmad R. Ganji (publisher: Prentice Hall), 2nd edition, 2003.
7. The Practice of Statistics by Dan Yates, David S. Moore, and Daren S. Starnes (publisher: W. H. Freeman & Co.), 2nd edition, 2002.
8. Practical Research: Planning and Design by Paul D. Leedy and Jeanne E. Ormrod, (publisher: Prentice Hall), 8th edition, 2004.
9. Handbook of Software for Engineers and Scientists by Paul W. Ross, (publisher: CRC-Press), 1st edition, 1995.

For the class, students will need the following free software: Scopy, LabView, Matlab, and Origin Pro. Follow the install instructions on the Canvas site. Class software will also be available in the EWS 3022 lab. Microsoft Office, specifically Word and Excel, Mathematica, and AutoCAD are recommended. Compilers for C or C++ and LaTeX are good to have though not needed for the course. These programs are generally available through the webstore. SAS JMP will only be used for a few weeks during the course and so the free 30-day trial is an option.