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# Adapting an Engineering Physics Measurements Laboratory to Incorporate Metrology Concepts

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# Adapting an Engineering Physics Measurements Laboratory to Incorporate Metrology Concepts

We are restructuring an existing required, two-credit advanced laboratory course around the subject matter of metrology and design of experiments. This is being done for several reasons: to provide a unifying theme for the course, which previously was a collection of unrelated experiments; to more clearly identify the purpose of the course to students, faculty, and outside observers; and to provide a clearer link between the skills a student gains in the course and the methods and skills desired by industry. The course – "Engineering Physics (EP) Lab" – is typically taken in a student's third year. It has advanced prerequisite courses, enabling more in-depth studies of physical phenomena and more sophisticated numerical analysis. Indeed, many Physics programs have a similar type of course. While an important part of the curriculum, it has lacked a "unifying idea" that helps explain the course to employers and students: it largely consisted of student groups rotating among challenging, but unrelated, experiments. Metrology, the science of measurement, is a core competency of STEM fields and plays a key role in modern engineering practice. It deals with several aspects that are common to (or readily adapted to) our laboratory course: (1) uncertainty in measurements (and its propagation); (2) traceability of measurements to the SI units via the National Institute of Standards and Technology (NIST); (3) calibration of a measurement instrument or process; (4) using design of experiments (DOE) for statistical analysis of variation in a process. In this paper we will describe how incorporating these ideas has complemented and enhanced the course so that it has an enhanced focus on quality of measurement. In addition to describing the course and its experiments, we will also report on the results of the first offering of this redesigned course and remark on future improvements.

## Introduction

The "advanced laboratory" course is a common feature of physics and engineering physics degree programs. A quick review of physics and engineering physics curricula in the U.S.A. shows courses with names such as "advanced experimental physics," "experimental methods," or simply "physics lab" or "engineering measurements. [1]" (Indeed, a "measurements lab" is also a common feature of mechanical engineering undergraduate curricula.[2]) Our institution, the University of Wisconsin-Platteville, is no different: the "engineering physics laboratory" is where students first undertake longer, more open-ended experiments than is done in the introductory physics sequence.

The EP Lab has a prerequisite of Modern Physics, and is typically taken in the first semester of the third year. It almost always is completed before our other lab course (Sensor Lab), it is the only specific course prerequisite for our capstone senior design course, and is an important part of our curriculum. The primary ABET outcomes associated with this course are [a] and [b]: "an ability to apply knowledge of mathematics, science, and engineering" and "an ability to design and conduct experiments, as well as to analyze and interpret data." Further, the program has assigned several secondary outcomes to this course: experiment design, effective communication, teaming, modern techniques and tools, ethics, and life-long learning [ABET outcomes c, d, f, g, i, and k]. The determination of particular science and/or engineering topics that should be assigned to this course has been a source of much discussion among the faculty over the years. Recently, we came to see the course's greatest strength as dealing with experimental design and uncertainty analysis, which while providing some guidance regarding "relevant" topics, still leaves things somewhat open.

However, the value of the course has been difficult to convey to those whom have not taken it. Though it is consistently valued by students and alumni, The name "Engineering Physics Lab" is vague and doesn't convey much to prospective employers or prospective students who are still formulating what Engineering Physics is. Thus, graduates have had a difficult time highlighting the course on a resume or in an interview setting: typically we justify courses based on their technical content, but in this course the content has shifted over the years from nuclear radiation to optics to advanced mechanics to interdisciplinary engineering problems (and back). To an outsider, the course can appear to simply lack focus. Of course, a course such as this in a physics curriculum is part of the reason that physicists have long been valued in industry: physicists' skills in problem solving and experimentation. In shifting from "physics" to "engineering physics," however, which at our campus is a hybrid of applied physics, electrical engineering, and mechanical engineering, the role of the advanced lab became less clear.

At the 2012 ASEE meeting, however, we learned of a key idea that has meaning in industry, ties together many of the key ideas already present in our course, and provides a framework for further development of the EP Lab course: metrology. Three measurement/quality organizations have put together a joint outreach effort: the Measurement Science Conference (MSC), the National Conference of Standards Laboratories, International (NCSLi), and the Measurement Division of the American Society of Quality (ASQ).[3] Inspired by discussions with representatives from these groups, we implemented changes in the next offering of EP Lab – less than three months later.

Metrology: Job Descriptions and Prospects

As the metrology outreach web site[3] takes pains to point out, metrology is not to be confused with meteorology. However, most scientists and engineers (and many students) are at least vaguely familiar with the term as having to do with measurement. More formally, metrology can be defined as the science of measurement and its application, including all theoretical and practical aspects of measurement, whatever the measurement uncertainty and field of application.[4] There exists a large national and international community of engineers and scientists that work in the metrology field. From an engineering perspective, though, perhaps the biggest misconception is not confusion with "meteorology" but that metrology might refer only to calibration of measurement instruments: i.e. a job associated with technicians, not engineers. This sentiment does not capture the full scope of metrology, however; while calibration is indeed an important job for a Calibration Technician, the jobs of Metrologists and Calibration Engineers have other responsibilities. The NCSLI and ASQ have prepared the following job descriptions for Metrologists and Calibration Engineers, submitted for inclusion in the U.S. Department of Labor's Standard Occupational Classification [SOC] system in 2010:[5]

> "Metrologists and Calibration Engineers
> Apply measurement science, mathematics, physics, and engineering principles to develop and/or design and support measurement systems, processes, and procedures for

calibration of inspection, measurement, and test equipment (M&TE) based on analysis of measurement problems, accuracy and precision requirements. Use statistics to analyze calibration standards and processes. Evaluate new calibration methods and procedures. Recommend calibration standards. Monitor compliance with calibration laboratory and/or departmental quality systems. May develop software to assist in calibration laboratory and/or departmental processes. May perform laboratory and/or departmental administration and management.

Work Duties

- Develop and/or design and support systems, processes, methods and procedures for calibrating M&TE based on analysis of measurement problems, accuracy and precision requirements;
- Analyze calibration standards and processes using statistics;
- Evaluate new calibration methods and procedures;
- Research calibration requirements in order to recommend calibration standards;
- Monitor compliance with laboratory and/or departmental quality systems;
- May develop software to assist in calibration laboratory and/or departmental processes; and
- May perform laboratory and/or departmental administration and management."

Therefore, a metrologist/calibration engineer must perform statistical analysis, design experiments and procedures, and determine means by which physical quantities can best be measured and monitored. There is a large overlap between the metrologist/calibration engineer and a quality engineer, with the metrologist/calibration engineer more focused on the execution and process of quality measurements and the design of experiments.

Metrology may further be divided into three main subfields:[6] (1) Scientific metrology; (2) Industrial metrology; and (3) Legal metrology. Scientific metrology deals with the organization and development of measurement standards and with their maintenance. This involves research and working at the "high end" of technology. Industrial metrology concerns the application of measurement science to manufacturing to ensure the suitability of measurement instruments and provide for their calibration and quality control of measurements.[7] Legal metrology is concerned with measurements that influence economic transactions and other law enforcement fields.

The job prospects in metrology and calibration are strong; this is because (1) several aspects of metrology – traceability, accuracy, precision, systematic bias, and evaluation of measurement uncertainty – are all critical parts of a quality management system;[8] (2) the reduction in metrology training by the armed forces, which has historically been the source of most of the skilled metrologists in the U.S.A.[9] (3) the large number of expected retirements in this field. Indeed, while the U.S. Bureau of Labor Statistics (BLS) does not collect employment or wage data specifically on metrologists,[10] the federal and Wisconsin Bureau of Labor Statistics show large projected growth in "Industrial Engineering" openings from 2008 to 2018.[11,12] These are largely driven by efforts in quality manufacturing and efficiency, which frequently involves metrology. Based on the recent hiring history of our EP alumni, we expect that many will find themselves in either scientific or industrial metrology. (In fact, with their interdisciplinary background, many EP graduates have already been working as quality engineers, which overlaps with metrology.)

Metrology: Key concepts added to EP Lab

The "metrology bible" is the International Vocabulary of Metrology (VIM), maintained by the International Organization for Standardization.[4] This 108-page reference provides a standard vocabulary for measurement-related terms such as metrology, calibration, traceability, and measurement uncertainty. Several of these ideas have been incorporated into the Engineering Physics Lab course. The first of these are <u>uncertainty</u> and <u>traceability</u>.

The VIM distinguishes between random measurement error, the component of measurement error that in replicate measurements varies in an unpredictable manner, and systematic error, the component of measurement error that in replicate measurements remains constant or varies in a predictable manner. In the particular case of uncertainty, the "Guide to the expression of uncertainty in measurement" (GUM)[13] focuses on the mathematical treatment of measurement uncertainty through an explicit measurement model under the assumption that the measurand can be characterized by an essentially unique value.

> The objective of measurement in the Uncertainty Approach is not to determine a true value as closely as possible. Rather, it is assumed that the information from measurement only permits assignment of an interval of reasonable values to the measurand, based on the assumption that no mistakes have been made in performing the measurement. Additional relevant information may reduce the range of the interval of values that can reasonably be attributed to the measurand. However, even the most refined measurement cannot reduce the interval to a single value because of the finite amount of detail in the definition of a measurand. The definitional uncertainty, therefore, <u>sets a minimum limit to any measurement uncertainty</u>. The interval can be represented by one of its values, called a "measured quantity value.[4]"

This concept of uncertainty meshes with another key idea from metrology, <u>traceability</u>. From the VIM, metrological traceability is the:

> property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty.

In other words, a traceable measurement is made with equipment that has been calibrated such that its measurements can be related back to "the" true measurement. In other words, traceability means that careful propagation of measurement uncertainty leads to the "true" value of a measurement, within its error bars. This concept proved to be a powerful motivator for students to doggedly pursue uncertainty throughout their measurements and calculations.

This led to some small but significant changes in how uncertainty was handled in the laboratory. These changes seemed to help the students work through uncertainty concepts and become more sophisticated in their handling of experimental uncertainty. For one, the uncertainty of an instrument was no longer merely related to the "most significant bit" on a digital display; it was determined by the manufacturer's specifications and by the time elapsed since the last calibration. For another, in the context of getting the "true" value, students did a better job of handling uncertainty. Students learned to take care to distinguish between random uncertainty and systematic uncertainty. For example, the idea of a 1.5% calibration error in a multimeter introduces an uncertainty "floor" that ultimately limits the accuracy of a measurement: averaging many measurements may reduce the random error to negligible levels, but one cannot say that the uncertainty is negligible, in light of the known limits of the instrumentation! By applying ideas and terminology from metrology, students came to see uncertainty as less of an abstract concept, and more as one that is directly related to industrial quality.

These ideas were also pursued by having students determine a simple quantity – such as the friction of a block on a surface, or the power dissipated in a resistor – by several experimental techniques and comparing the techniques to determine the "best" approach. For example, based on the manufacturer's specifications of their instruments, plus the relative magnitudes of current, voltage, and resistance, it was found that not using the resistance measurement led to more precise measurement of power dissipation.

We did not fully implement the concept of traceability, since the rapid implementation meant that we did not have time to purchase reference standards other than a calibrated, NIST-traceable voltmeter (none of the original lab equipment had been calibrated since its initial purchase). Plans for the next offering of the course will be discussed below.

For similar reasons, we did not do much with a key third metrology term, calibration. The VIM defines calibration as

> operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication

In other words, calibration is a *comparison* of two measurement devices or systems, one of known uncertainty (the standard) and one of unknown uncertainty (the test equipment to be calibrated). This concept was left for the next course offering, with the next annual budget.

Finally, a key idea from metrology and quality measurements that was already part of EP Lab is the Design of Experiments method. Design of Experiments, or DOE, is a scientific/engineering approach that allows the researcher to model a complex process based on a "relatively small" amount of empirical data. The DOE method is a key part of the body of knowledge (BOK) for both the "Six Sigma[14]" and the "Certified Quality Engineer[15]" certifications from the ASQ. For example, the "process" could be an environmental stress screening process where the "inputs" are humidity, thermal cycle, vibration, and time, and the "output" may be number of defective parts. Since the creation of EP Lab in the late 1990s, students have developed a two-level, three-factor, full-factorial model of a catapult. Recently, with our realization of DOE as a key component in metrology and measurement quality, we added a term project to develop a DOE model of any (instructor-approved) process of their choosing. This experience was extremely valuable, as students learned that their open-ended systems could very well be strongly nonlinear – and not well served by DOE unless they carefully confined the range of their input parameters.

## Reflection and future implementations

We feel that starting to adapt our upper level measurements lab around the theme of "metrology, measurement quality, and design of experiments" has served us well. Continuing this process will make the course more recognizable to employers as something valuable, and will make it easier for students and faculty to convey its value to others. This "metrology/quality" approach to a measurements lab brings together the "win" in experimental techniques with the "win" in relating them directly to issues relevant to employers: measurement quality and design of experiments. Further, students are more able to see the relevance of the course to their future career paths: we feel they approached this year's topics with renewed energy compared to previous years' offerings.

The most obvious addition to the course will be the addition of NIST-traceable instrumentation to the lab. This will enable calibration and traceable measurements of temperature, length via gage blocks) and time (via a function generator), and students will be able to address the traceability of their measurements. If time permits, students will also undertake a calibration process – though this may instead be moved to different required course, Sensor Lab, to build on and reinforce ideas from EP Lab.

Another area that will be developed arose when students began applying complicated fits to their data – and failing. For example, the frequency response of a driven, damped harmonic oscillator was not found to match the expected model. The result for this is simple, in hindsight: the model did not include several "real" aspects of the experiment. This could include small levels of friction and nonlinear damping, but could also include such things as offsets – i.e., systematic errors – in the measurement tools. This led to frustration on the students' part, but also shows a means to actually identify systematic errors in the measurement process, and to subsequently develop experiments and analytical methods that are less sensitive to these errors. This will be explored in a more directed fashion next year, as it forces the students to confront the limitations of both their models and their measurements.

Finally, we will more carefully use terminology from the metrology and quality fields (i.e. the VIM and GUM) so that students will better speak the language of these fields and relate their skills to future employers and colleagues. For example, based on Six Sigma's and Certified Quality Engineer's Body of Knowledge, more advanced DOE concepts and terminology will be introduced, such as randomization, replication, blocking, interaction, confounding, and resolution – terms used by these quality certifications and by the National Institute of Standards and Technology (NIST).[16]

## Summary

We are adapting a "upper level measurements lab" around the theme of metrology and design of experiments. This will make the course more recognizable to employers as something valuable, and will make it easier for students and faculty to convey its value to others. This will unite proper advanced experimental technique with concepts directly relevant to employers: measurement quality and design of experiments.

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[1] See, for example, Southeast Missouri State University, Cornell University. (Curricula downloaded January 2013).
[2] See, for example, Washington State University; University of Pittsburgh; Massachusetts Institute of Technology, and the University of Wisconsin-Platteville. (Curricula downloaded January 2013).
[3] http://www.metrologycareers.com (downloaded January 2013).
[4] "International vocabulary of metrology – Basic and general concepts and associated terms (VIM)," Joint Committee for Guides in Metrology (JCGM), 3rd edition (2008). Freely available at http://www.bipm.org/utils/common/documents/jcgm/JCGM_200_2012.pdf .
[5] "Metrology Human Resources Handbook," prepared by the NCSLI Workplace and Professional Development Committee, published by NCSL International (2010).
[6] "Types of Metrology", (www.metrologycareers.com), downloaded January 2013.
[7] Fishnell, J. V., Hovakemian, A., Sugg, D., Gentry, E., "Navy Metrology Engineering Education Outreach: Inspiring and Educating Students about Careers in Metrology," American Society for Engineering Education (ASEE) Annual Conference (2012).
[8] http://en.wikipedia.org/wiki/Metrology (downloaded January 2013).
[9] M. L. Taylor, "Status of Metrology Education in North America (a lost science?)," Metrologist Magazine, pp. 20-24, April 2012.
[10] Drew Liming, "Metrology Careers: Jobs for Good Measure," Occupational Outlook Quartlerly, pp. 10-15, Fall 2009.
[11] Bureau of Labor Statistics Employment Projections, http://www.bls.gov/emp/. Downloaded January 2013.
[12] Wisconsin WorkNet Occupation Projections, http://worknet.wisconsin.gov/worknet/downloads.aspx?menuselection=da&pgm=occprj Downloaded January 2013.
[13] "JCGM 100:2008 Evaluation of measurement data — Guide to the expression of uncertainty in measurement (GUM),"Joint Committee for Guides in Metrology (JCGM), 2008 version corrected 2010. Available at: http://www.bipm.org/utils/common/documents/jcgm/JCGM_100_2008_E.pdf
[14] "Six Sigma Black Belt Certification - Body of Knowledge," Part VIIA – Design of Experiments (DOE). http://prdweb.asq.org/certification/control/six-sigma/bok . Downloaded January 2013.
[15] "Quality Engineer Certification - Body of Knowledge," Part H – Design and Analysis of Experiments. http://prdweb.asq.org/certification/control/quality-engineer/bok . Downloaded January 2013.
[16] NIST/SEMATECH e-Handbook of Statistical Methods, Section 5.7: A Glossary of DOE Terminology. http://www.itl.nist.gov/div898/handbook/NIST . Downloaded January 2013.