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# Incorporating Adult Learning Methods and Project Based Learning in Laboratory Metrology Courses

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## Abstract

Measurement scientists work in calibration laboratories throughout the world. Yet, there are few university level courses available that cover the critical topics needed for performing and analyzing precision measurements – at the desired level. Many continuing education courses of this nature are taught by National Metrology Institutes (NMIs) and original equipment manufacturers (OEMs) of precision measuring equipment and measurement standards. What often happens in the measurement community is that subject matter experts and scientists who best know about measurements are asked to teach courses and tutorials, but most do not have a background in educational models or adult education principles.

Over the past 3 years, the National Institute of Standards and Technology (NIST) Office of Weights and Measures (OWM) - has been providing train the trainer and adult education courses and opportunities to our subject matter experts to help them better analyze, design, develop, implement, and evaluate our technical training content. The goal has been to enable students to achieve a higher level of cognition on the Bloom's Taxonomy scale (e.g., application versus knowledge). Highlights of the key resources that have been incorporated into the instructional design process are presented as potentially useful for the professional development of instructors this is particularly useful for instructors without a background in educational theories and models. Some highlights of instructional design concepts are covered in one section to provide value added for those who do not have formal training or education in educational concepts.

This paper also provides case study examples focused on laboratory metrology. The case study design integrates learning objectives, activities, assessment methods, and adult learning to create effective project based learning activities and a case study in a Fundamentals of Metrology course. The activities and examples used in the course and shared in this paper illustrate some of the essential knowledge and skills needed by measurement professionals and those engineers who interact with calibration staff to better perform and/or analyze precision measurements. These examples, and portions of the case study, have been implemented in a training laboratory, as well as in non-laboratory conference center classrooms, and could easily be implemented with varying and limited resources in engineering courses.


## Course Description and Background

The Fundamentals of Metrology course is a 40-hour, team and project based course. It includes approximately 60 percent of the time spent in activities related to the main case study. Appendix A includes a table that shows the course topics and key knowledge, skills, and acronyms that are covered and provide a foundation of knowledge needed for more specific courses that are taught on various measurement parameters (e.g., mass, volume, thermometry, forensics, etcetera). As determined during the needs assessment and reassessments of the prior course structure, it was observed that the topics from this course were integrated into each of the other measurement courses and resulted in redundant and overlapping content. The Fundamentals of Metrology seminar now introduces the participant to measurement foundation concepts such as measurement systems, units, measurement uncertainty, measurement assurance, metrological traceability, basic statistics, and how each topic fits into a laboratory quality management system that complies with the ISO/IEC 17025[1] documentary standard. Many calibration and testing laboratories are accredited to this particular documentary standard throughout the world. Additional topics that are covered include overall laboratory management and laboratory quality management systems and specific discussions of the laboratory requirements for proficiency testing, calibration report generation, software verification and validation, and management reviews. Topics are covered in the course using a variety of measurement disciplines and case studies so that the participants will be able to apply the concepts to any measurement discipline upon completion. Each module is presented using a mixture of training approaches including lecture, hands-on exercises, team projects and presentations, case studies, and discussion (among others). In subsequent courses on Mass Metrology and Volume Metrology, we are now able to build on concepts that were covered in the Fundamentals of Metrology course without completely covering each topic again, eliminating much of the previous duplication.

Prerequisites for the course include having a demonstrated knowledge of basic mathematics and completion of a number of reading assignments. It was also determined during needs assessment that OWM instructors were spending excessive time helping students with remedial mathematics tasks. Successful completion of mathematics pre-examination is often required in the continuing education environment; however, course titles or numbers with designated passing levels could be used in a university setting. In the metrology career field, most professionals already have a scientific, mathematics, or engineering degree. It has been found through instructional experience that most working professionals, even in these fields, have historically not been adequately exposed to the concepts covered in this course. This situation could change in the future through sharing these concepts among university professors. At this time, application of these concepts or case studies into an engineering curriculum could be done at either an introductory or advanced level, depending on the prior knowledge of the students.

Pre-reading assignments given to the students include the following materials:

- *ISO/IEC 17025, General Requirements for the Competence of Testing and Calibration Laboratories*[2];
- *Beginner's Guide to Measurement*[3]; and
- *Introduction to Measurement in the Physics Laboratory, a Probabilistic Approach*[4].

Students are assessed throughout the course based on active participation in the group projects, question/answer responses, discussions, presentations, measurement results, and projects that are turned in for review. Follow on workplace assignments are given to some students (based on

NIST OWM requirements for laboratory recognition.) These workplace assignments are part of a laboratory auditing program, where problems include analysis of measurements made in their own laboratories based on concepts covered in the course, plus demonstration of measurement proficiency, and preparation of formal calibration reports. The successful completion of the *OWM* courses and follow on problems is often an employment requirement and is also required for laboratory recognition by NIST Office of Weights and Measures.

## Instructional Design Concepts

Note: Information in this section on instructional design concepts is provided as background on OWM's course evaluation and development process. It will be of most use for readers or professors who have a science and/or engineering background and limited formal educational background. Based on experience and observations working with subject matter experts, it is value-added for the scope of this paper to include this information for metrology instructor audiences. However, if this section is overly obvious, the reader might consider skipping to the section on Fundamentals of Metrology – Course Activities.

The NIST Office of Weights and Measures training program has invested in a number of educational and training efforts for technical staff as a part of a strategic effort to become an Authorized Provider of continuing education units through the International Association for Continuing Education and Training (IACET). A number of formal instructional design concepts have been and are being incorporated into continuing education courses for working measurement professionals. Some key concepts include the assessment and use of the ADDIE instructional system design model, Bloom's Taxonomy, project based learning, adult learning concepts/facilitation techniques, and the use of worksheets during learning event planning to ensure matching of learning objectives, activities, and instructional assessment methods in courses. Each of these topics has an abundance of literature available freely on the World Wide Web, therefore, only a brief description and is made here, with some specific assessments of measurement instruction, along with reference sources.

### *ADDIE Instructional System Design Model*

"The instructional system design approach is a behavior-oriented model that emphasizes the specific skills to be learned and the learner's abilities to demonstrate these skills."[5] The five steps of the ADDIE model are analysis, design, development, implementation, and evaluation. Through experience with continuing education opportunities in metrology, it has been found that many subject matter experts often prefer one-on-one mentoring. Because they are experts and know the technical content quite well, they often think they can easily translate that knowledge to instruction. So, if asked to teach a course, they usually begin by developing a set of presentation slides without adequate consideration of analysis and design steps, and later during the course, they often miss evaluation of the student's learning.

Many copies of the ASTD Info-Line handout *Teach SMEs to Design Training* have been provided to the OWM program's metrology instructors. This publication provides quick, easy to understand guidance on each of the five phases of the ADDIE model.

1. Analysis – the audience is identified during the analysis phase. The essential outcomes of the training are identified in this phase, sometimes in conjunction with the participant, but more importantly the employer. During a metrology trainer session held in Mexico in 2012, several metrology instructors expressed frustration with the diversity of student knowledge level and level of experience of students attending their courses. A quick review of their metrology course descriptions resulted in identifying an audience that was much broader than they ideally wanted in each course.
2. Design – terminal and intermediate learning objectives are clearly defined during the design phase. A quick review of learning objectives submitted for conference abstracts that the author has reviewed from many metrology subject matter experts reveals that the learning objectives are often a simple outline of "what will be covered in the course." The instructor's objective is to cover the material, versus considering what the student should know or be able to do at the conclusion of the learning event. For adult learners in the workplace, it is essential to consider what they need to be able to know or do on the job, or what their employers need them to be able to know or do.
3. Development – instructional methods and activities are selected during this phase, to consider maximum effectiveness. It is not uncommon to hear a subject matter expert say "I'm preparing for a course next month and am working on making presentation slides." As a result of this approach, the development of the course is limited primarily to lecture, with possibly some demonstrations or discussions which fall on the low side of Bloom's Taxonomy. In a field such as metrology, where the professional must be able to perform hands on measurements or measuring instrument evaluations, lecture-based training events rarely achieve the desired objectives of application. Similarly, increased effectiveness of activity based learning or project based learning has been demonstrated in engineering studies.
4. Implementation – this phase deals with the logistics and presentation style/skills of actually delivering or better yet, facilitating, the learning event.
5. Evaluation – this phase is often included in each of the other phases to assess whether or not the intended outcome will be met. But, when considered in light of student performance during the course, it refers to the assessment methods used by the instructor to appraise whether the student is learning. It asks the question "is the student making good measurements?"

A more in depth text book on this topic is one by Chuck Hodell[6], as used in an Instructional System Development Graduate Program at the University of Maryland, Baltimore County.

*Bloom's Taxonomy*

One common statement made to new OWM metrology students is that "we don't care how much you know if you don't apply it back in your laboratory." Then, in learning about Bloom's Taxonomy and the relationship between the levels of cognition and learning methodologies and assessments, this idea was reinforced! Bloom's Taxonomy refers to the matching of desired levels of cognition with desired learning objectives. A more expanded version of the following table was provided to OWM instructors during a train-the-trainer session and became a staple for the technical training staff. In addition to identifying the learning objective taxonomic level, the process helps demonstrate that selected activities and assessments are selected, aligned, and appropriate at each level. In OWM metrology courses, student performance needed to be at the application level, but lectures were primarily used for delivery. The lecture/test format is true in many educational environments. However, review of project and activity based learning research provided a "light-bulb moment" for the OWM program as it illustrated that matching learning objectives and activities at the application level could achieve the desired results.

**Table 1. Alignment of Bloom's Taxonomy to Learning Activities and Assessment Methods.**

| **Bloom's Taxonomy Levels** | Knowledge | Comprehension | Application | Analysis | Synthesis | Evaluation |
|---|---|---|---|---|---|---|
| **Activities** | Lecture<br>Video | Questions<br>Discussions | Demonstrations<br>Practice | Problems<br>Case Studies | Simulations | Projects |
| **Assessment** | Tests | | Essays, Reports, Case Studies, Simulations | | | |

*Project-Based, Activity-Based Learning*

During the metrology course re-design project, there were a number of references OWM instructors reviewed with respect to modifying training methodologies (Knight[7], Hake[8], and Woods[9]), to include more projects and activities to achieve a higher level learning objective.. The Knight reference focuses on applications in physics experiments in a project based learning that by design are quite similar to the OWM metrology examples and provided insight in our experimental approach. Just prior to the 2011 American Society for Engineering Education (ASEE) annual conference in Vancouver, the OWM had completed a series of beta testing for the new Fundamentals of Metrology course. During the beta tests, student participants vehemently expressed frustration with the new activity based course, which departed significantly from the predominantly lecture based methods that had been used in the past. While attending the ASEE conference, the keynote speaker explained Hake and Woods research which was very similar to the emotional stages of grief. It was another "light bulb moment" when OWM instructors realized that students were experiencing the same phenomenon.

*Adult Learning*

As noted earlier, metrology professionals must be able to perform hands on measurements or measuring instrument evaluations. Adults generally want to identify immediate application of their learning to the workplace. Hands-on learning, activities, and case studies provide opportunities for metrology professionals to practice new skills in a safe learning environment, thus they are better prepared to apply the concepts and skills back on the job. During an OWM train-the-trainer session, a facilitation technique called the *Five Steps of Adult Learning*[10] was presented. This instructional method fits well with problem solving and project/activity based learning. For activities of sufficient length, this technique is regularly used and provides for effective processing and debriefing of the activity. The five steps are shown in the following table, from a Flask Exercise[11] metrology case study example. Note that provided questions are open ended, and are not answerable with yes or no responses, which lead to thoughtful discussions.

**Table 2. Five Steps Example.**

| | | |
|---|---|---|
| 1 | Set up the Activity | The set-up of measurement activities ideally includes something that is interactive and selected to get to the right level of Bloom's Taxonomy. Be sure to clearly tell participants what they are to do, how they will or won't work in teams, what the ground rules are, and why the activity is important (without giving away the intended discovery). |
| 2 | Participants Perform the Activity | Adults need to be as involved as much as possible and use as many senses as possible. In fact, many demonstrations or videos that do not allow adults to actually do something themselves only use sight and sound, but not touch or smell. Additional activities might include entering data into a spreadsheet, working in teams to come up with a list, evaluating a procedure, brainstorming, or analyzing a case study. |
| 3 | Participants Share and Interpret Their Reactions | This step helps learners identify what happened to themselves and others. It is intended to help them understand the exercise and its point. Here are some example questions:<br>- What did you observe during the measurement processes?<br>- What was frustrating during the exercise?<br>- What additional information did you need to know to successfully complete the measurement?<br>- Did you observe others doing something different that could impact their measurement or yours?<br>- Identify one or two challenges in following this procedure. |
| 4 | Participants Identify Concepts | This step helps participants reflect on what was learned. This helps them get beyond doing a fun exercise to considering how the effort might be important for other tasks. Questions include:<br>- How does the information from the good measurement practice relate to your experience in the Flask Exercise?<br>- What else is important in the process?<br>- What principles are important to remember?<br>- How can good technique or bad techniques contribute to good/bad measurement results?<br>- What other procedures might use this principle?<br>- How can you integrate this concept into your overall laboratory operation? |
| 5 | Participants Apply Concepts to Situations in Their Laboratory | This is the WIIFM principle in action (that's "What's In It for Me"). Adult participants need to be able to apply these concepts back on the job and see the relationship between the activity and what is important about being successful in the laboratory. Questions might include:<br>- In what situations might some of these principles be important in your laboratory? |

| | | |
|---|---|---|
| | | - What are the consequences of not paying attention to some of these good measurement principles?<br>- What improvements might you make in your laboratory based on our review and discussion?<br>- In what situations could the application of these concepts improve your measurement results?<br>- How does this fit with your experience? |

In addition to the Five Steps of Adult Learning, active participation is also expected in the course and points are awarded based on correct answers, insightful questions, correct answers to quick quizzes, and successful team activities. The point system provides immediate feedback to students regarding their mastery of a topic and tracks their active engagement throughout the learning event.

*Learning Event Planning*

As a part of the OWM analysis and planning efforts, a Learning Event Planning Worksheet was created that includes a number of categories for planning, including constraints, instructor needs, matching of the learning objectives with activities and assessment methods, as well as planning a tentative agenda. The section shown in Table 3 assists in assessing the planned approach based on the desired level of the learning outcomes. For example, at times, an initial activity that includes a lecture might not achieve the desired objectives and additional work needs to be done on the design and development process.

**Table 3. Learning Event Planning Worksheet.**

| Learning Outcome | Instructional Method (Activity) | Assessment Method |
|---|---|---|
| Seminar participant will be able to correctly select: the laboratory standards, procedures, and equipment for the process. | Discussion, demonstration, laboratory practice exercises, and case study | Observations and discussions with questions and answers.<br><br>Participant responses will provide insight into their level of understanding of the concept. |

## Fundamentals of Metrology – Course Activities

First, the room is set up in pods/blocks of three to four students each as initial teams. The laboratory is divided into stations that will match the classroom teams. The class is limited to 12 students at this time, though could be expanded to 16 with additional laboratory equipment and stations. The three stations in the laboratory have identical equipment and measurement standards that are presented in Module 4. Points are given for the various activities to capture and track levels of participation (which is one of the stated criteria for successful completion of the course).

**Major Project**

The major project in this course is a laboratory measurement project that incorporates a number of elements and is built upon in every module. A brief description of the project is that pennies are measured – qualitatively and quantitatively with a variety of measurement tools. The final student deliverable is a calibration report that complies with the requirements of ISO/IEC 17025, section 5.10. The measurement exercises take about 10 hours in total with regular group discussions and debriefing. Items other than pennies could be chosen as the measurement activity. NIST OWM considered manufactured or assembled parts, but chose pennies due to the low cost, ready availability and size. After considering the various exercises used in this project, one could easily modify the activities and project to use something from the university engineering environment. More specifics about the project itself will be covered in Module 4. Key activities and outcomes will be discussed chronologically according to the structure of the course and modules noted in Appendix A.

**Module 1 - Introduction**

After covering essential laboratory safety guidelines and emergency instructions, Module 1 begins with a brief lecture and reference to the International Vocabulary of Metrology (VIM)[12]. There are three key activities covered during the introduction. The first is an introduction activity where students introduce themselves to every other person in the room, share something that is not work related, and also share their years of experience. These facts are collected and later used to divide the class into teams (based on ensuring balance in each team of more experienced and new metrology professionals). The next activity is done within each team with a time limit. The question posed on the presentation slide is: "what is measurement?" Students are asked to make a list on the team's flip chart in a two minute time interval of everything they can think of that might be measured. The lists are debriefed and individuals in each team are given participation points; the specific definition from the VIM is provided during the debriefing discussion.

The next activity is begun immediately after debriefing. First, a retractable pen is shown to the class and the instructor asks: "What is the length of this pen?" Various answers are given: some answers are in inches, some are in centimeters, while some are in other measurement units. Then the instructor points out that the answer is that the length is from one end to the other end, and that students should respond with "with the pen point or clicker end in or out?" or "from where to where on the pen?" Each of these options would provide a different length on the pen. This leads into the definitions of *measurand* (the item being measured) and how important it is to be very specific in defining what is being measured. Then, a clock is shown on the slide and the slide asks: "what is the current time?" Students are asked to wait once this slide is shown and the instructor will indicate a time to write down the answer. The instructor captures the student times on the whiteboard. Students often answer the time shown on the clock on the slide, some use their cell phones, some use the clocks on their computers, some use their watches, and some use the clock on the wall. Some answer in hours and minutes, some answer hours, minutes, and seconds, some include AM or PM, some report answers in military/24-hour time. The debriefing points out that the question "what is the current time?" was not specific enough to define the measurand of interest. This exercise also leads into a discussion of why there was variability in the responses using an Ishikawa (e.g., cause/effect or fishbone) diagram with the key categories being: facilities, equipment, standards (different timing devices used with different resolution), staff (expertise in measuring time accurately), and operations (procedures, instructions). The definition of *calibration* is also covered in this module (to point out that a calibration measurement result will be needed for their final project and is different than an *adjustment*).

**Module 2 – Measurement Systems**

Module 2 includes a lecture covering the history and overview of "who's who" in the measurement science world beginning with the International Bureau of Weights and Measures and various international, regional, and national measurement and standards organizations. Additional definitions are provided in this module and specific references are provided for correct use and reporting of measurement units and symbols. It is NIST OWM's observation among scientists and engineers in general, that correct use of measurement units and symbols is very poor and very inconsistent. Because students in this course are considered "measurement professionals" when they work in a calibration or testing laboratory, the idea that their work must accurately reflect the use of correct measurement units and symbols is reinforced. The general idea that is reinforced is that "if people don't see proper units and symbols on your work, how can they consider your measurement results with any credibility?"

The course is covered entirely in the International System of Units (SI or metric system) and students must submit all answers in metric units, though they will be required to perform some unit conversions from U.S. Customary units. Therefore, a quick review is provided on dimensional analysis concepts and a brief calculation exercise is conducted.

Good laboratory practices are also covered in this module (e.g., pencils are not permitted because the writing is not permanent, measurement results must be written legibly and measurement units are always included with correct unit symbols).

**Module 3 – Laboratory Management (and Quality Systems)**

Module 3 is primarily activity driven with several exercises conducted in the teams or instructor review of materials in the student notebook. The objective of this module is for students to be able to identify the sections and high-level requirements of the ISO/IEC 17025 documentary standard. This document is the main ISO/IEC standard used throughout the world by testing and calibration laboratories; especially those that are accredited (third party assessment). In general terms, for those familiar with "ISO 9000" this is a similar kind of standard for laboratories, which also requires demonstrated proficiency. The joke in quality circles is that a company could have an ISO 9000 registration for creating cement life jackets and as long as they documented what they do and do what they have documented, they can get registered. That is not supposed to be the case with ISO/IEC 17025 accreditation – demonstration of expertise and proficiency are requirements.

Each team is provided with a deck of index cards in activity one. They are asked to place the cards in order of the typical laboratory workflow. Card titles include: accept calibration item from submitter, assign personnel, select standards, select procedure, identify which laboratory room should be used, determine measurement results, calculate uncertainty, assess the measurement results, adjust measuring result on the item, create final report, and return calibration items to submitter. Additional cards include things like, laboratory quality manual, procedures, internal audit reports. Cards are shuffled and teams are expected to engage in discussions about placing the items in order to achieve the "best flow" for their laboratory. They are also asked to put some cards in a separate pile if they reflect what is required as part of the laboratory infrastructure versus specific measurement flow. During the debriefing, the instructor asks teams to sacrifice one card from their selection to consider minimum impact on the final result. The point of the exercise is to show that all of these cards are part of the major category headings of the ISO/IEC 17025 standard and that sacrificing one component will be detrimental to the quality of their measurement results.

The standard is reviewed at this point and two key sections are highlighted, one on the topic of document control and one on records management. Both document control and records management are part of the laboratory operations, but according to the standard their function is distinctly different. Documents tell you what you are going to do or guide the user and records are the objective evidence (proof) of what was done. This topic is covered due to the lack of understanding by what is meant by objective evidence, which is sought during the various types of audits that are required for a fully functioning calibration laboratory.

Two activities are covered at this point. One in which the teams create lists of documents or records on their flip charts (that are saved throughout the week for later reference) and one in which another deck of index cards is given to the teams and they have to sort the cards into three piles: documents, records, and possibly both (e.g., a calibration report for your own standards is a document, but if being provided to the customer, it might be a record).

The concept of a laboratory measurement scope is presented here and again reviewed at the beginning of Module 4. The measurement scope typically includes a measurement parameter, range, uncertainty, and possibly specific test methods. For example, a calibration laboratory might perform mass calibrations from 1 kg to 1 mg, with uncertainties at each nominal value. A biomedical laboratory might evaluate lead in blood using a specific procedure.

**Module 4 – Measurements**

The penny exercise is introduced in this module. The scenario is presented as follows: "we have been tasked to work for the Coinstar ™ Company to help refine their measurement processes for the coin counting machines." Review the Coinstar patent descriptions to consider the many engineering concepts that could be considered here! An alternative approach is that "we've been asked to work on a contract for the U.S. Mint as they refine their penny production process (NIST OWM obtained input on specifications, tolerances, and production processes from the U.S. Mint staff in developing the scenario). *The Beginner's Guide to Measurement* that was assigned as pre-reading comes in very handy as students are asked to reflect and ask questions about the exercises throughout this module. They are given an opportunity to consider "what questions do you have for the customer?" and "what questions do you have for your management?" Instructors record the questions on the whiteboard, but provide limited answers throughout each phase of this process and only give answers at the last possible moment during the measurement exercises (which again take about 10 hours in total).

*Step 1. Research the specifications for a new measurement scope parameter.*

When a laboratory wants to add a new measurement to their scope, they often will need to determine what they already have in place versus what they need to have in place. Documentary standards, test methods, and measuring instrument specifications might guide their investigations. Two pages of penny specifications are provided to the students to read. Students are asked to identify questions and approaches to the measurements that they might need to consider, to evaluate what procedures might be used.

*Step 2. Assess the laboratory and measurement station.*

Students are then asked to go to the laboratory and identify all of the equipment, standards, and resources in their measurement stations. A notebook in each station provides information on care, handling, and operating instructions for all equipment and standards. The notebook also includes calibration reports for all measurement standards that are provided. Each station includes: 2 balances (one with a 0.001 g resolution, the other with 0.000 01 g resolution), 2 calipers [one digital (0.01 mm) and one analog (0.001 in)], environmental station with temperature, pressure, humidity sensors, a thermometer with two thermistor probes, magnifying glasses, mass standards (100 g to 10 mg), ceramic gauge blocks (25 mm to 1 mm), aluminum weighing dishes, and forceps. Students will have been given homework assignments to read the Standard Operating Procedure 1, for the *Preparation of Test/Calibration Reports*[13]. Students are told to record the laboratory environmental conditions. They are also asked to record everything from their measurement station that they think might be important for creating their calibration report and to discuss potential procedures. They are also given time to read the manuals and practice making measurements to be sure they know how to use and measure with each piece of equipment. They are told that their team will need to identify and suggest a "best approach" to the measurement problems and to consider a "measurement equation." Again, they are asked to share their questions for "the customer" and for "management."

At this point, students are told that they will have *at least* mass, thickness/diameter, and volume to be included on the reports for the customer.

*Step 3. Conduct an initial inspection of submitted test items.*

Students are given an initial "sample" of 30 pennies. We consider samples and populations during the discussion on statistics. But at this stage, students are asked to consider how they will sort and track them for the calibration report and to be able to uniquely identify each penny for the report. They are given an index card with 1 cm x 1 cm grids marked on it for identifying their sample items and given a case they can use for transporting the pennies between the laboratory and classroom (but without specific instructions). They are told to inspect all of the pennies in their sample and to identify as many measurement variables and ways to define and describe these pennies as they can think of and record the data in their notebooks. They are told to think "outside of the box" and to consider both qualitative and quantitative types of measurements.

They are asked to estimate the values they expect to observe (using SI measurement units) in the laboratory and consider how to organize the pennies to prevent them from being mixed up. Students are also asked to identify the measurand(s) that will be measured for the customer, and to again ask their questions for the customer and for management. Then students work in teams to create a list on their flip charts of "all possible things they might measure" on the pennies as they add the parameter to their scope. Many of the items on their list will either be included on the calibration report or will be considered again when discussing the validated procedure that will be used and/or the uncertainty of their measurements.

After inspecting the pennies, qualitative issues are often raised about how to uniquely identify each penny (since serializing and cleaning them is not permitted, just as it is not permitted for precision mass standards). The Sheldon Scale is then presented to students. The Sheldon Scale is a 70-point scale for grading coins, developed by Dr. William Sheldon in 1949 (http://coins.about.com/od/coingrading/f/sheldon_scale.htm). A slightly modified form of the Sheldon Scale has become the de facto standard for grading U.S. coins today, and is used by the major third party grading services when assigning a grade to a coin. The adjectival grading system was the predecessor to today's 70-point grading scale, and the adjectival terms are still used to help clarify the numeric equivalent. Examples of diamond grading (color, cut, and clarity) and maple syrup grading are presented as additional examples. NIST OWM uses a Vermont maple syrup grading kit for demonstration, which was obtained from the Vermont Weights and Measures Division[14].

*Step 4. Evaluate measurement capabilities and measuring instruments.*

Students are instructed to make ten measurements of a "special penny" that is available in their station on each balance and using each caliper and to consider how they will evaluate their balances and calipers with the mass standards and gauge blocks in their stations. The data from this exercise is later entered in a spreadsheet that has been designed for the course and which contains multiple worksheets to illustrate various concepts. The data used to select the best or most appropriate instrument, consider statistical tools for helping assess the instruments and making a decision, and evaluate the measurement uncertainty that will be needed for the calibration report. They are reminded that each person in the team needs to make measurements and record all data (with all units) as they may not be in the same teams later in the week.

Debriefing this step requires each team to share their approach for incorporating the standards into the measurement process and the exact steps they followed in performing the measurements. Each team's approach is written on the whiteboard and the entire collection of approaches is assessed and a final procedure is developed and approved by the instructor. This consolidated or consensus procedure is assigned a name and printed from the printable whiteboard to become their documented procedure for subsequent measurements. Concepts regarding which standards to use and instrument accuracy and linearity are presented here (to bracket the measurement results).

At this stage, additional discussions of the measurements also take place and any additional questions are recorded. Answers are provided at this stage about measurement tolerances and additional procedural questions are answered. A handout is given that includes the Sheldon Scale, additional measurement guidance (where and how to measure the samples) and the measurement tolerances required by the customer.

*Step 5. Measure submitted test items.*

Participants are told to measure each of the "oldest" five pennies and "newest" five pennies in their sample for their calibration report. In addition, they are asked to measure the "special penny" at their station and that four pennies will be circulating through the teams as a "proficiency test". They know at this stage, that their calibration report will report fifteen pennies. Environmental measurements are made and recorded as well.

*Step 6. Determine test item volume.*

Participants are instructed to individually identify three possible approaches that might be used to determine the volume of each penny. As a group, the class discusses which method will likely give the best measurement results. A handout with measurement equations is distributed at this point that includes: three volume formulas, a simple mass equation that makes use of the corrections for the mass standards, a mass equation with buoyancy corrections, a simple dimensional equation that includes use of the gauge blocks, and a dimensional equation that uses temperature corrections for the linear coefficient of expansion. This is the last measurement process that is performed in the project.

**Module 5 – Traceability**

Metrological traceability is a key concept that all measurement professionals must be able to know and explain to others. ISO/IEC 17025 requires a statement regarding traceability to be on most calibration and test reports. This module includes a brief lecture along with demonstration examples from real world laboratories that illustrate how metrological traceability can be documented for various types of measurement parameters. During the lecture, the seven essential elements of metrological traceability are identified and listed on a flip chart as students read and identify them from the VIM definition. NIST Good Measurement Practice (GMP) 13[15] is provided to the students and covers the VIM definition and the seven essential elements in greater depth. The GMP also provides examples of what a "traceability hierarchy" should look like for several measurement processes.

The instructor demonstrates sketching out the "mass" traceability hierarchy for the penny exercise on a flip chart or white board. At this time, students are asked to review their measurement notes and measurement results for the penny exercise and to use the mass example as a model to sketch out a detailed metrological traceability hierarchy for their dimensional measurements. To be considered complete, it must include all seven essential elements. The activity is debriefed to identify best practices and gaps (points are awarded).

**Module 6 – Statistics**

During the penny measurement exercises, students gathered data for their pennies from at least two balances (one three place and one five place) and at least two calipers (analog and digital). Various statistical concepts are presented in a mini lecture and demonstrated. Students review additional worksheets where they entered their initial measurement data and discuss the calculated results for mean, standard deviation, F-test, and t-test for each of their measurements. The output of this information is used in the uncertainty assessments.

**Module 7 – Measurement Assurance**

Module seven includes a lecture that covers concepts on measurement assurance and statistical process control. The ISO/IEC 17025 standard covers quality assurance of the measurement process in section 5.9 and several standard operating procedures are available in the NIST OWM program (SOP 9, 17, 20, and 30). The key concept is that of incorporating a *check standard* into the measurement process to obtain ongoing statistical data on a *surrogate* artifact over time (instructions are given that the surrogate should represent the sample items as closely as possible).

There are two activities in this module. One is a team card matching exercise that considers two examples that are matched up with the five examples given in the ISO/IEC 17025 standard. Each team's result is debriefed with the class. During the second exercise, each team is provided a set of 6 possible check standards and asked to identify and list the pros/cons of the best three options in their set and to use this information to determine the best check standard. The sets consist of: a small watch style battery that is about the same diameter as a penny, three washers of similar diameter, one steel, one brass, and one polypropylene, a lead weight (fishing sinker), and a plastic button about similar diameter as the pennies. Some students pull a penny out of their pocket/bag at this point for comparison. The debriefing exercise has each team present their best three options and pros and cons of each choice. The class solution is that the “special penny” in their station will be the best check standard. Some teams suggest this option.

The repeated measurements that were made on the “special penny” are considered at this point, as there is another tab in their spreadsheet with a control chart on it. Calibration values were in each station notebook for these “special pennies” to consider bias and measurement errors in the next section on uncertainty.

**Module 8 – Uncertainty**

Uncertainty analysis in a calibration laboratory must follow the *Guide to the Expression of Uncertainty in Measurement*[16]. NIST Standard Operating Procedure 29[17] is also referenced for this section. Definitions are covered in a lecture. The eight step process of SOP 29 is covered, as it applies to the penny exercise, with the main activity including students working through their own data and examples for each of the eight steps in the process. The definition of metrological traceability includes a component of uncertainty. ISO/IEC 17025 requires uncertainty statements on calibration and test reports. The final calculated uncertainties for each team are compared for validation.

**Module 9 – Proficiency Testing**

Proficiency testing methods and analysis tools are presented in a brief lecture. One worksheet in the template spreadsheet includes assessment of the special penny using statistical tools that are common in laboratory proficiency testing. The concept of root cause analysis is presented with additional resources. The measurement data students obtained during the measurement exercises are considered as a group assessment of proficiency.

**Module 10 – Software Verification and Validation**

Students were provided with a template spreadsheet with their course resources and they began using it to record values during the Module 4 measurement exercises. During the various activities up to this module, errors will have been identified by the students. Software verification and validation concepts are covered in a short lecture, and NIST Standard Administrative Procedure, 10[18] and Form A (an appendix) are discussed as a tool to evaluate the course spreadsheet. During the measurement and data entry process, students should have observed several “spreadsheet errors” that have been purposefully incorporated in the spreadsheet to illustrate the importance of laboratory software validation and its contribution to accurate measurement results, which are ultimately included on the calibration report.

In proficiency testing of the laboratories that are a part of the NIST OWM program, software errors have been identified as one of the top five causes of failures in laboratory proficiency tests. Students are given time to review the spreadsheet further and note errors using Form A.

**Module 11 – Management Reviews**

A brief lecture on management review topics required in the ISO/IEC 17025 standard is presented. Some of the topics that were previously covered during the course are components of a management review. Items that were included throughout the course were not the complete contents of a management review but did include:

- Adequacy of policies and procedures. For example, a new procedure for the penny measurements was developed;
- Results of interlaboratory comparisons or proficiency tests;
- Evaluation of laboratory workload and scope. For example, several measurement parameters were added to the laboratory scope ;
- Additional standards, equipment or other resources that might be needed to conduct or improve the measurement processes were identified. For example, the laboratory might need to use a micrometer instead of calipers.
- Results of measurement assurance (control chart evaluations); and
- Demonstration of staff competency and training effectiveness.

At this point, students conduct an analysis activity on the ISO/IEC 17025 standard elements to identify implementation gaps and describe the resulting impact on laboratory measurements. . Students are given two to three of the twenty five major sections of ISO/IEC 17025 in a table that includes the headings shown below. Most students will have identified specific examples of problems throughout the week that they can use for this exercise. The most common potential negative impact cited is that customers will receive bad measurement results on their calibration reports.

**Table 4. ISO/IEC 17025 Impact Exercise.**

| Section Number | Simplified Section Heading | Possible Omission | Potential Impact | Examples |
|---|---|---|---|---|

## Module 12 – Calibration Reports

The primary product provided by a metrology laboratory is a calibration or test report, which was presented early in Module 3. The students have been told since the first day, that their primary product (course "deliverable") will be a calibration report. The calibration report must have correct units symbols, accurate data and appropriate wording. Reading SOP 1 was assigned as an early homework activity. Students were advised at the beginning of the measurement project that they would be required to develop a calibration report that was compliant with ISO/IEC 17025 section 5.10 and NIST SOP 1. A discussion of calibration reports may be conducted earlier than Module 12 if there seems to be a good time to engage the students in this topic; it is included between modules 5 and 11. There are two activities at that point. One is called the "black dot exercise" and the other is a "team competition to identify errors."

The instructor draws a black dot on a flip chart paper during a break; then when everyone returns, the instructor asks the group "what do you see?" The activity is debriefed by discussing the customer reaction when they find a "black dot" or error on the calibration report and how this can impact lab credibility. Students work in teams in a two minute brainstorming competition to identify all of the types of errors they have found on calibration reports. The exercise is debriefed to highlight that many potential error sources exist and that careful review is essential when producing high quality reports. The discussion reveals that many items that are listed are not found in section 5.10 requirements.

Individual student calibration reports are printed out on the morning of the last day of class and between modules 10 and 12. Students exchange what they believe to be their final calibration report with another team member. The students use a checklist based on ISO/IEC 17025 and SOP 1 to evaluate the reports, including the proper use of unit symbols and a review of common errors. Students are given time to make additional edits before they are turned in. Module 12 is actually interspersed among the other modules in this way. Final calibration reports are reviewed with summary examples of remaining problems (usually presentation of measurement units and symbols). The product students turn in is often better than what is routinely seen from many operational laboratories.

At the review point in the course, a handout like Appendix A is given to the students for review and to ask questions. Depending on the overall class active participation point totals and measurement results, either a written examination is given, or a final jeopardy-like team competition is conducted to review the course.

**Conclusions**

The project and various exercises used in the NIST OWM Fundamentals of Metrology course require students to get beyond regurgitating memorized answers to lectures and go beyond simply following established procedures. While the major project activity for this course is based on laboratory measurements, additional learning activities include lectures, assigned reading, calculations, discussions, presentations, and evaluations. Students must identify the measurement problems, ask questions, engage each other, and consider options at each step in the measurement process, and weigh the advantages and disadvantages at each step. The instructor is able to easily assess whether students are participating, whether learning objectives are met, and whether each student is successful. Through this project approach, students also use and demonstrate skills that are needed in the laboratory environment such as: team work, preparing and giving presentations, accurate communications, and trouble-shooting.

Past OWM measurement courses were specific to one or more measurement disciplines with content overlapping from course to course (which served to reinforce content, but resulted in basic information being presented multiple times to the same students). The primary teaching methods in the past included significant time in lecture, plus laboratory demonstrations by the instructor, followed by and hands-on practice following procedures, with limited higher-level thinking required. Now, students are expected to build upon the knowledge level of Bloom's Taxonomy gained through reading and listening to lectures to the application and analysis levels through the use of more complex activities such as team discussions, debate, hands-on measurements, calculations, evaluation of data from case studies, and evaluation of various approaches and final results. OWM has observed anecdotal improvements (as yet unmeasured) in student achievement in subsequent courses covering specific calibration methods in mass and volume metrology.

As noted earlier, student resistance was observed as the shift to a project based approach was made. Initially, students trained under the previous curriculum and methods resisted participating in the exercises designed to promote higher level thinking with statements such as "don't make us think about it, just tell us what to do." However, students new to the curriculum readily engaged in the learning process. In fact, one student who took the Fundamentals of Metrology course early in 2011 attended a course on ISO/IEC 17025 immediately following our one-week course. When she later attended a Mass Metrology Seminar, she commented "I didn't realize how much I appreciated your style and approach of teaching and learning until I attended that other course." She had been apprehensive about taking the mass course, but went on to do fine, because that course also uses activity based learning and projects, each phase building on prior activities.

Feedback from the OWM team of instructors is equally positive. The Intermediate Metrology Course had been in place since the 1980's and the final class was presented in December 2012. The course content is now replaced by the measurement parameter specific courses. Two primary contract instructors have said something along the lines of "I really didn't realize the significance of the improvements in the other courses and relative student participation and achievements until we presented this [Intermediate Metrology] course again and we were able to compare the difference."

## Appendix A – Fundamentals of Metrology

*(Numbers in parentheses refer to sections in the ISO/IEC 17025 documentary standard.)*

| | Module | Definitions/Knowledge | Acronyms | Tools/Skills |
|---|---|---|---|---|
| 1 | Introduction | measurand, measurement, measurement units, calibration | VIM | Identify components of a Cause and Effect Diagram |
| 2 | Measurement Systems | World Metrology Day, seven base units, measurement standards, documentary standards, supplier evaluation, laboratory scopes, ISO/IEC 17025, specifications and tolerances, good laboratory practices, dimensional analysis | BIPM, SI, NMI, NIST, CIPM (MRA), RMO, ILAC (MRA), AB, ISO/IEC, GMP, SOP, GLP | Identify components of laboratory Scope, Convert measurement results and units to the International System of Units (SI) |
| 3 | Laboratory Management | document or record, objective evidence | QMS | Identify major sections of ISO/IEC 17025 standard, Conduct Gap Analysis and Identify Impact of Gaps |
| 4 | Measurements | care and handling of balances, calipers, mass standards, gage blocks (and associated laboratory equipment), reference values | | Study Specifications, Inspect Laboratory, Equipment, and Standards, Perform Contract Review, Record Data, Perform Careful Measurements, Consider Method Validation, Create Measurement Equation, Identify corrections and uncertainties from calibration reports |
| 5 | Traceability | metrological traceability, metrological traceability chain, traceability hierarchy, seven essential elements, types of standards | | Create Metrological Traceability Hierarchy, Assess for Traceability Components, Create Traceability Statement |
| 6 | Statistics | statistics, accuracy, precision, degrees of freedom, confidence intervals, probability, distribution types, population, sample | | Calculate: Mean, Standard Deviation, F-test, and t-test, Look up table references, Compare sample data sets |
| 7 | Measurement Assurance | measurement assurance | | Assess process control, Select a suitable check standard, Identify examples for approaches to Measurement Assurance (5.9), Identify Plan-Do-Check-Act cycle, Relate components of four-step Understand-Model-Measure-Monitor cycle |
| 8 | Uncertainty | uncertainty, coverage factor, type a, type b, standard uncertainty, combined uncertainty, expanded uncertainty | GUM, EURACHEM | Identify eight Steps of the uncertainty analysis and reporting process; Specify, Identify, Quantify, Convert, Combine, Expand, Evaluate, Report |
| 9 | Proficiency Testing | proficiency testing, interlaboratory comparison, normalized error, normalized precision, ISO/IEC 17043 | | Assess data agreement with reference, Assess uncertainties, Evaluate bias/offset |
| 10 | Software Verification and Validation | verification, validation | FDA, NASA, SSFM (NPL), SAP, RP | Assess software for common errors (beyond data sets) |
| 11 | Management Reviews | management review | APLAC | Identify components (4.15), Describe benefits of a management report |
| 12 | Calibration Reports | | | Identify requirements (5.10), Assess reports, Create a compliant calibration or test report |

## Endnotes and References

[1] ISO/IEC 17025, General requirements for the competence of testing and calibration laboratories, 2010. It is available through several documentary standards resellers, including ISO, IEC, directly, or the American National Standards Institute (ANSI) in the United States. Since this is a copyrighted standard, it is not freely available. Special NOTE: As the U.S. Member Body of the International Organization for Standardization (ISO), ANSI has been authorized to provide, upon request, complimentary access for students and faculty to selected standards currently available in the ISO collection. If needed, certain standards from the International Electrotechnical Commission (IEC) may also be made available. These collections are comprised of nearly 20,000 standards, which can be made available to faculty and students in all disciplines in institutions of higher learning throughout the United States.

[2] ISO/IEC 17025, General requirements for the competence of testing and calibration laboratories, 2010. It is available through several documentary standards resellers, including ISO, IEC, directly, or the American National Standards Institute (ANSI) in the United States. Since this is a copyrighted standard, it is not freely available. Special NOTE: As the U.S. Member Body of the International Organization for Standardization (ISO), ANSI has been authorized to provide, upon request, complimentary access for students and faculty to selected standards currently available in the ISO collection. If needed, certain standards from the International Electrotechnical Commission (IEC) may also be made available. These collections are comprised of nearly 20,000 standards, which can be made available to faculty and students in all disciplines in institutions of higher learning throughout the United States.

[3] This publication was developed by the National Physical Laboratory in the United Kingdom. This Beginner's Guide is for those that are new to measurement, to provide an introduction to metrology (the science of measurement). Part One provides an overview and history of measurement - it explains the fundamental concepts and basic facts about the world of measurement. Part Two provides more practical information that affects many areas of measurement - it explains why measurement issues should be addressed. It is available free online: http://www.npl.co.uk/publications/beginners-guide-to-measurement/

[4] This is a manual for the teaching of measurement in the introductory physics laboratory based on the ISO-recommended probabilistic framework (Guide to the Expression of Uncertainty in Measurement, GUM) for the interpretation and analysis of data. It is available free online: http://www.phy.uct.ac.za/people/buffler/labmanual.html

[5] Teach SMEs to Design Training, American Society for Training and Development (ASTD) Info-Line, June 2001. Available at http://www.astd.org.

[6] Hodell, Chuck, ISD From the Ground Up (2nd Ed): A No-Nonsense Approach to Instructional Design, ASTD Press; 2nd edition (September 20, 2006). Available from http://www.amazon.com.

[7] Knight, Randall D., Five Easy Lessons, Strategies for Successful Physics Teaching, Addison-Wesley, San Francisco, CA, 2004.

[8] Hake, Richard R., Interactive-engagement vs traditional methods: A six-thousand student survey of mechanics test data for introductory physics courses, http://www.physics.indiana.edu/~sdi/ajpv3i.pdf

[9] Woods, Donald R., Problem-based learning: how to gain the most from PBL, 2000 2nd ed., also: Helping Your Students Gain the Most From PBL, McMaster University, Canada, http://www.tp.edu.sg/pbl_donaldwoods.pdf

[10] This five step process is based on resources provided by The Training Clinic (http://www.thetrainingclinic.com/) and has been adapted to metrology concepts in the example questions from a hands-on laboratory exercise with weighing a 200 mL flask filled with distilled water.

[11] Harris, G., "Train the Trainer: Five Steps of Adult Learning Activities", NCSLI Metrologist, July 2010. Available upon request from the author (gharris@nist.gov).

[12] International Vocabulary of Metrology (VIM): International Vocabulary of Metrology – Basic and General Concepts and Associated Terms, JCGM 200:2012, (JCGM 200:2008 with minor corrections), This corrected version of the 3rd edition cancels and replaces JCGM 200:2008 (see the JCGM 200:2008 Corrigendum) and the 2nd edition, 1993. Available free: http://www.bipm.org/en/publications/guides/vim.html.

[13] Standard Operating Procedure 1, Recommended Standard Operating Procedures for Preparation of Test/Calibration Reports, 2012. From NISTIR 6969, Selected Procedures for Mass Calibrations. Available free: http://www.nist.gov/pml/wmd/labmetrology/upload/SOP_1_20120229.pdf

[14] http://www.vermontmaple.org/grades.php (no endorsement implied or intended).

[15] Good Measurement Practice 13, Good Measurement Practice for Ensuring Metrological Traceability, February 2012. From NISTIR 6969, Selected Procedures for Mass Calibrations. Available free: http://www.nist.gov/pml/wmd/labmetrology/upload/GMP_13_20120229.pdf

[16] Evaluation of measurement data – Guide to the expression of uncertainty in measurement, JCGM 100:2008 (GUM 1995 with minor corrections), Available free: http://www.bipm.org/en/publications/guides/gum.html

[17] SOP 29, Standard Operating Procedure for the Assignment of Uncertainty, From NISTIR 6969, Selected Procedures for Mass Calibrations. Available free: http://www.nist.gov/pml/wmd/labmetrology/upload/SOP_29_20120229.pdf.

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