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# "THE ROLE OF LABORATORIES AND ITS SELF AUDIT IN ENGINEERING EDUCATION"

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## ABSTRACT

*The function of the engineering profession is to manipulate materials, energy, and information, thereby creating benefit for humankind. To do this successfully, engineers must have a knowledge of nature that goes beyond mere theory—knowledge that is traditionally gained in educational laboratories. Over the years, however, the nature of these laboratories has changed. Every laboratory must become comfortable with being audited. A self-audit conducted internally is an excellent tool for the lab to prepare itself for any audit, identify problems, test execution, and simulate an actual audit experience. Conducting a rigorous self-audit that simulates an actual audit also helps to establish a culture that supports an on-going state of preparedness in the laboratory. This paper describes the history of some of these changes and explores in some depth a few of the major factors influencing laboratories today. In particular, the paper considers the lack of coherent*

*learning objectives for laboratories and how this lack has limited the effectiveness of laboratories and hampered meaningful research in the area. A list of fundamental objectives is presented.*

*This paper is also deals with the importance of self audit regarding the laboratories and how we can carry the self audit.*

***Keywords: laboratories, learning objectives, history of laboratories ,laboratory overview, sample handling and storage in advance of testing, instrument maintenance and calibration, lab audit process.***

## I. INTRODUCTION

Engineering is a practicing profession, a profession devoted to harnessing and modifying the three fundamental resources that humankind has available for the creation of all technology: energy, materials, and information.

The overall goal of engineering education is to prepare students to practice engineering and, in particular, to deal with the forces and materials of nature. Thus, from the earliest days of engineering education, instructional laboratories have been an essential part of undergraduate and, in some cases, graduate programs. Indeed, prior to the emphasis on engineering science, it could be said that most engineering instruction took place in the laboratory. The emphasis on laboratories has varied over the years. While much attention has been paid to curriculum and teaching methods, relatively little has been written about laboratory instruction. As an example, in surveys of the articles published in the *Journal of Engineering Education* from 1993 to 1997, it was found that only 6.5 percent of the papers used laboratory as a keyword. From 1998 to 2002, the fraction was even lower at 5.2 percent [1]. One reason for the limited research on instructional laboratories may be a lack of consensus on the basic objectives of the laboratory experience. While there seems to be general agreement that laboratories

are necessary, little has been said about what they are expected to accomplish. In most papers about laboratories, no course objectives or outcomes are listed, even though it is not unusual for the author to state in the conclusion that the objectives of the course were met. An accepted set of fundamental objectives for laboratories, as set out in this paper, would help engineering educators focus their efforts and evaluate the effectiveness of laboratory experiences. It is useful to distinguish among three basic types of engineering laboratories: development, research, and educational. While they have many characteristics in common, there are some fundamental differences. These differences must be understood if there is to is agreement on the educational objectives that the instructional laboratory is expected to meet. Practicing engineers go to the development laboratory for two reasons. First, they often need experimental data to guide them in designing and developing a product. The development laboratory is used to answer specific questions about nature that must be answered before a design and development process can continue. The second reason is to determine if a design performs as intended. Measurements of performance are compared to specifications, and these comparisons either demonstrate compliance or indicate where, if not how, changes need to be made. While a development laboratory is intended to answer specific questions of immediate importance, research laboratories are used to seek broader knowledge that can be generalized and systematized, often without any specific use in mind. The output of a research laboratory is generally an addition to the overall knowledge that we have of the world, be it natural or human made. When students, especially undergraduates, go to the laboratory, however, it is not generally to extract some data necessary for a design, to evaluate a new device, or to discover a new addition to our knowledge of the world. Each of these functions involves determining something that no one else knows or at least that is not generally available. Students, on the other hand, go to an instructional laboratory to learn something that practicing engineers are assumed to already know. That “something” needs to be better defined through carefully designed learning objectives if the considerable effort devoted to laboratories is to produce a concomitant benefit. Laboratory instruction has been complicated by the introduction of two phenomena in the past two decades: the digital computer and systems of distance learning, particularly over the Internet. The digital computer has opened new possibilities in the laboratory, including simulation, automated data acquisition, remote control of instruments, and rapid data analysis and presentation. The reality of offering undergraduate engineering education via distance learning has caused educators to consider and discuss just what the fundamental objectives of instructional laboratories are. These discussions have led to new understandings of laboratories and have created new challenges for engineering educators as they design the education system for the next generation of engineers. Laboratory instruction has not received a great deal of attention in the past few years. As will be noted later, however, and as has been discussed in other writings [2], several factors currently contribute to a reawakening of interest in the subject.

## II. HISTORICAL ROLE OF ENGINEERING INSTRUCTIONALLABORATORIES

Engineering is a practical discipline. It is a hands-on profession where doing is key. Consequently, prior to the creation of engineering schools, engineering was taught in an apprenticeship program modeled in part after the British apprenticeship system. These early engineers had to design, analyze, and build their own creations—learning by doing. Engineering education, even today, occurs as much in the laboratory as through lecture [3]. However, from the onset of formal engineering education, a tension between theory and practice evolved. During these early years the focus was clearly on practice. The first engineering school in the United States, the U.S. Military Academy, founded at West Point, N.Y. in 1802 to produce and train military engineers [4], was based in part on the French curricular model of mathematical rigor. It was also coupled with practice, striking a balance of sorts between theory and practice Civilian schools soon followed and developed curricula that, as the founder of Rensselaer Polytechnic Institute stated, existed "for the purpose of instructing persons, who may choose to apply themselves, in the application of science to the common purposes of life [5]." Applying science to everyday life requires both theory and hands-on practicum. While the former lends itself to classroom learning, the latter can only be learned and practiced in the physical laboratory. During the middle of the nineteenth century, many engineering schools sprung up, including Cornell (1830), Union College (1845), Yale (1852), MIT (1865), and many others. Fueled by the Industrial Revolution and the Morrill Land Grant Act of 1862, these institutions developed curricula that placed heavy emphasis on laboratory instruction and taught a new generation of young engineers how to design and build everything from turbines to railroads and canals to telegraph lines and chemical plants. To support the integral laboratory curricula, new physical structures were being built on the campuses of these institutions to house the engineering laboratories. At MIT, a new laboratory specifically for mechanical engineering was built in 1874. Worchester Polytechnic Institute dedicated Stratton Hall in 1894 to house the expanding mechanical engineering department and its engineering laboratories. When the American Society of Civil Engineers was founded in 1852, one of its early technical divisions was the Surveying Division. Surveying became one the many undergraduate course areas that provided a practical work environment. Laboratories and fieldwork were clearly a major part of the engineering education experience. The accreditation process has had an impact on engineering laboratories, although the effect has often been indirect. Engineering accreditation in the United States started with the American Institute of Chemical Engineers (AIChE) [6]. Concerned about maintaining

quality, the AIChE established a system for evaluating chemical engineering departments and, in 1925, issued a list of the first fourteen schools to gain accreditation.

Engineering programs required science and mathematics, but drafting and laboratory and fieldwork remained integral parts of the curriculum through the end of the Second World War. After World War II many of the great inventions that occurred as a result of the war were developed by individuals educated as scientists rather than engineers.

Many engineering schools began graduating engineers who were steeped in theory but poor in practice. While engineering programs became more theoretical, industry continued to require individuals who possessed more practical skills. To provide these practically trained individuals, many institutions developed programs in engineering technology. Since many of these technologists filled positions formerly held by engineers, they often received that title, causing confusion between engineering andproblematic and ECPD, to help distinguish the professions, began accrediting

two- and four-year technology programs. Around 1980, engineering societies underwent a major reorganization, and ECPD became the Accreditation Board for Engineering and Technology (ABET). ABET became the organization responsible for engineering and technology accreditation and maintained separate accreditation tracks for programs in engineering and those in technology. With clearly defined boundaries, it became clear that engineers were not adequately prepared in laboratory techniques. New criteria were created that required adequate laboratory practice [10]. Laboratory plans that included instrumentation replacement and refurbishment were now required for everyp program. In addition to the Grinter report, the American Society for Engineering Education has produced other reports on engineering education and made recommendations for changes and improvements.

As technology has advanced, systems have developed for measuring ever more complex parameters to ever increasing levels of precision and accuracy. These systems come at an increased cost for both acquisition and maintenance. They also require more broadly educated technicians who are difficult to hire and who command higher salaries. Engineering department budgets are not always adequate to meet the needs of a modern instructional laboratory, especially those requiring significant amounts of hands-on involvement. As so many engineering programs have developed an increasing interest in research, the faculty reward system, in the opinion of many, has shifted away from recognizing contributions to undergraduate education and toward rewarding research productivity. While this has helped to create an outstanding academic research enterprise, it has drawn the attention of faculty away from such time-intensive activities as developing and evolving instructional laboratories. Though it is clear that a quality undergraduate program that includes a quality laboratory experience requires the effort and dedication of some of our best faculty, it is less obvious how the reward system will be altered to recognize curricular achievements. Universities continue to address this issue.

The rapid evolution of the personal computer and its integration into the laboratory have helped to offset some of the costs of requiring expensive equipment and have improved the laboratory experience through computer use in data acquisition, data reduction, design assistance, and simulations. The role of computers in the engineering laboratory is covered in more detail in sections IV and V below.

## III. SIMULATIONVERSUSREAL

### 3.1. Experimentation

The use of technology to simulate physical phenomena probably found its first serious use in the “Blue Box” developed by Edwin Link in the 1928, now an ASME National Landmark. The “Link

Trainer” flight simulator was used to train thousands of military aviators before and during World War II, saving millions of dollars and more than a few lives. Today, simulators are used to deliver training for all kinds of activities, from piloting sophisticated aircraft or ships to operating nuclear power plants or complex chemical processing facilities. Today, simulation software programs are available that accurately emulate many technical and physical processes. These software programs play an important role in engineering education. Two significant software developments used to simulate engineering processes have had a revolutionary effect on engineering education: finite element modeling (FEM) and simulation program with IC emphasis (SPICE).

FEM software was an outgrowth of a structural analysis tool developed in the 1940s to help engineers design better aircraft. SPICE was an outgrowth of an effort by Ron Rohrer and his student, Larry Nagel, at the University of California, Berkley to develop a circuit simulation program for their work on optimization. In some sense, SPICE and FEM have become virtual laboratories.

Students can design a circuit or a mechanical structure and then submit it to SPICE or FEM to determine their design's characteristics "experimentally" through the use of digital simulation. These programs did, however, have limitations. Real devices and materials are intricate and difficult to model accurately. Since simulation is only as good as the model used, it is essential that it be accurate. Some of the simulations are based on simplified models that fail when analyzing complex circuits or structures [43]. Understanding the limitations of simulations compared to real processes is a key factor in their use. In education, simulation has been used to provide illustrations of phenomena that are not easily visualized, such as electromagnetic fields, laminar flow in pipes, heat transfer through materials, and electron flow in semiconductors or beam loading [44]. Since simulators essentially execute mathematical equations and since we are able to develop reasonably accurate mathematical models of the physical phenomena we study in engineering laboratories, it is natural that simulators have been used as an adjunct to or even as a substitute for actual laboratory experiments. There are numerous uses of simulation in the laboratory. _ Simulations can be used as a pre-lab experience to give students some idea of what they will encounter in an actual experiment [45]. This can improve laboratory safety by familiarizing students with the equipment before actually using it. It also can result in significant financial savings by reducing the time a student or team needs on real—and expensive— laboratory equipment, thereby reducing the number of laboratory stations required. _ Simulations can be used as stand-alone substitutes for physical laboratory exercises and then be assessed by comparing the performance of students who used simulation and those who used traditional laboratories [46]. It was found that the former group scored higher on a written exam. The students who did the simulations were also required to perform two physical laboratory exercises after they had done the simulations. Judged on the basis of time needed to complete those exercises, the two groups performed about the same although the times of the students who used the simulations exhibited a significantly higher standard deviation. _ Simulations are useful for experimental studies of systems that are too large, too expensive, or too dangerous for physical measurements by undergraduate students [47–49]. Early criticisms of simulations were that they were too rigid, the models were too unrealistic, or simulated results really did not adequately represent real-world systems and behavior. Efforts to make laboratory exercises based on simulations more realistic include a number of innovations and efforts, for example, by inserting budget and time constraints into the problem specifications [50] or by incorporating statistical fluctuations into the model to enhance realism. Indeed, building a simulation that is appropriately—and sometimes surprisingly—random can alleviate some of the concerns that simulations do not represent the real world. It is generally agreed that computer simulations today cannot completely replace physical, hands-on experiments. With continuing increases in computing power and efficiency, however, that goal will certainly be approached more closely in the future. The example of flight simulation systems capable of giving pilots valuable experience with normal flight—as well as with problems they might encounter should encourage engineering educators to continue to develop better laboratory simulations. Pilots who experience the stress of a simulator training exercise can attest to the realism that simulation can provide.

## IV. THE FUNDAMENTAL OBJECTIVES OF LABORATORIES

As history has shown, there has not been general agreement on the objectives of engineering instructional laboratories nor any real efforts to define a comprehensive set until now. Indeed, many educators have not explicitly defined objectives at all and many of those who have, do so in terms that make it difficult to assess whether those objectives have been achieved. Either the profession's requirements for specificity were not very strict or there was a faith that a system that had always worked would continue to work as long as it was given a certain amount of nourishment.

There are at least two problems with this state of affairs. First, designing a laboratory experience without clear instructional objectives is like designing a product without a clear set of design specifications. Something useful might result but, at worst, it may not be what was really desired and, at best, the process will be exceedingly inefficient. Second, innovation will be difficult because there are no targets to inspire change and no standards by which the changes may be judged. This last problem has become clear with the advent of programs offering undergraduate engineering degrees, including laboratories, using the Internet or other distance learning technologies.

As mentioned earlier, the lack of a clear understanding of the objectives of instructional l aboratories became clear—and vexing— to ABET when distance education programs began inquiring about accreditation. Officials of ABET recognized that, while well-understood— if not completely explicit—criteria exist for evaluating the cognitive component of engineering education, no such understanding existed for laboratories. This apparent limitation in defining a clear purpose for the role of laboratories in a program handicaps the ability of an institution to determine if its curricular objectives for a degree are being fully met. To help resolve this problem, ABET approached the Sloan Foundation, a charitable foundation that has given considerable support to the development of distance-learning systems, particularly in higher education. The Foundation agreed to fund a colloquy to assemble a group of experienced engineering educators to determine objectives for evaluating the efficacy of distance-delivered engineering laboratory programs. As the steering committee designed the colloquy program, they concluded that the question was not "What are the objectives of distance-delivered laboratories?" It was "What are the fundamental objectives of engineering instructional laboratories?" independent of the method of delivery.

## V.THE FUNDAMENTAL OBJECTIVES OF ENGINEERING INSTRUCTIONAL LABORATORIES

All objectives start with the following: "By completing the laboratories in the engineering undergraduate curriculum, you will be able to…."

Objective 1: Instrumentation. Apply appropriate sensors, instrumentation, and/or software tools to make measurements of physical quantities.

Objective 2: Models. Identify the strengths and limitations of theoretical models as predictors of real-world behaviors. This may include evaluating whether a theory adequately describes a physical event and establishing or validating a relationship between measured data and underlying physical principles.

Objective 3: Experiment. Devise an experimental approach, specify appropriate equipment and procedures, implement these procedures, and interpret the resulting data to characterize an engineering material, component, or system.

Objective 4: Data Analysis. Demonstrate the ability to collect, analyze, and interpret data, and to form and support conclusions. Make order of magnitude judgments and use measurement unit systems and conversions.

Objective 5: Design. Design, build, or assemble a part, product, or system, including using specific methodologies, equipment, or materials; meeting client requirements; developing system specifications from requirements; and testing and debugging a prototype, system, or process using appropriate tools to satisfy requirements.

Objective 6: Learn from Failure. Identify unsuccessful outcomes due to faulty equipment, parts, code, construction, process, or design, and then re-engineer effective solutions.

Objective 7: Creativity. Demonstrate appropriate levels of independent thought, creativity, and capability in real-world proble solving.

Objective 8: Psychomotor. Demonstrate competence in selection, modification, and operation of appropriate engineering tools and resources.

Objective 9: Safety. Identify health, safety, and environmental issues related to technological processes and activities, and deal with them responsibly.

Objective 10: Communication. Communicate effectively about laboratory work with a specific audience, both orally and in writing, at levels ranging from executive summaries to comprehensive technical reports.

Objective 11: Teamwork. Work effectively in teams, including structure individual and joint accountability; assign roles, responsibilities, and tasks; monitor progress; meet deadlines; and integrate individual contributions into a final deliverable.

Objective 12: Ethics in the Laboratory. Behave with highest ethical standards, including reporting information objectively and interacting with integrity.

Objective 13: Sensory Awareness. Use the human senses to gather information and to make sound engineering judgments in formulating conclusions about real-world problems. It is interesting to note that the objectives cut across all domains of knowledge. It was no surprise that many deal with knowledge in the cognitive domain. This has long been the province of engineering educators and is an area in which everyone seems to be comfortable. So, the first five objectives dealing with cognition—Instrumentation, Models, Experiment, Data Analysis, and Design— were expected. Then, two were specified that involve the psychomotor domain: Psychomotor (the ability to actually manipulate apparatus) and Sensory Awareness.

Finally, the remaining objectives have a cognitive part but also include a significant component of the affective domain, i.e., behavior and attitudes: learn from failure, creativity, safety, communication, teamwork, and ethics in thelaboratory. Exposing students to all three of these domains is necessary to produce an effective engineer.

It is also interesting to compare these recently described fundamental objectives to the “roles” defined by Edward Ernst in a seminal paper more than twenty years ago [65]. “In my examination of the undergraduate engineering laboratory, I have identified three roles or objectives as major ones. First, the student should learn how to be an experimenter. Second, the laboratory can be a place for the student to learn new and developing subject matter. Third, laboratory courses help the student to gain insight and understanding of the real world.”

The current objectives serve as an expansion of this list. These roles (or goals) can provide a philosophical basis for laboratories.

The more specific objectives are needed to provide clear guidance in developing instructional laboratories. Using these objectives as a framework, laboratory developers and educational researchers can identify the specific objectives that their work is expected to achieve and have confidence that those objectives have been accepted by a significant portion of the engineering education community. In the two or more years following the colloquy, the organizers conducted a limited survey of engineering educators to determine if there was general agreement that the objectives were applicable and exhaustive. They presented their findings in several high-visibility venues and discovered that, while there was general agreement that the objectives were exhaustive, there was considerable spread in opinion concerning whether they were all essential. Further investigation, including better segregation by discipline, is still neede

## VI .LAB SELF AUDIT

Successful laboratories operate in this state at all times. This discussion provides a guide to the self-audit of a laboratory. Laboratory systems independent of an actual test result are reviewed beginning with the laboratory organizational structure through sample collection, analytical testing, and record retention. Areas of interest are identified including specific function, procedures, practices, records, and staff compliance with procedures. Topics discussed include the laboratory audit process, relevant audit documents and references, laboratory procedure availability, document requests by auditors, and audit training for personnel. An approach to gap identification, analysis, and prioritization of mitigation projects is presented. A case study is given describing an actual regulatory audit of an analytical quality control (QC) laboratory and its supporting research and development (R&D) laboratory.

## VII. IMPORTANCE OF AUDIT

Every organization must become comfortable with being audited. Regulatory audits by global agencies, International Organization for Standardization (ISO) Registrar certification audits, external customer audits, and internal quality assurance (QA) audits happen frequently. Some may come at a moment's notice while others are planned weeks in advance. The key to a success is to make sure your area is always prepared for an audit. A functioning laboratory must function in a state of readiness on a daily basis. However, audits and inspections of the laboratory are often not anticipated. Audits that start in a distant site's conference room usually lead to the manufacturing floor and ultimately involve one or more laboratories at the site. Organizations often have a designated internal function whose sole purpose is to conduct internal audits. These may be very rigorous audits; the personnel conducting such audits are usually very well experienced. These audits are stressful events for the lab since the results may be communicated to high-level personnel in the organization. To prepare for these internal audits as well as the aforementioned regulatory, ISO, and other audits, self-audits conducted by the laboratory personnel are recommended.

This is an excellent tool for the lab to prepare itself for any audit, identify problems, test execution, and simulate the actual audit experience. Conducting a rigorous self-audit or that simulates an actual audit also helps to establish a culture that supports an ongoing state of preparedness in the laboratory.

The following discussion provides a guide to the self-audit of a laboratory.

Audits maybe conducted in different ways. This approach addresses the laboratory systems independent of anactual test result. It begins by identifying the major elements of a laboratory operation listed accordingto a typical sequence of activities. It then identifies areas to assess to determine the readiness of the laboratory for an outside audit. The elements of a laboratory operation are listed below beginning with the laboratory organizational structure through the sample collection, testing, and record retention:

- Laboratory overview
- Sample collection
- Sample receipt in the lab
- Sample handling and storage in advance before testing
- Sample testing
- Instrument qualification
- Instrument maintenance and calibration
- Test method and sampling procedure development
- Test method validation
- Laboratory technical training
- Data treatment
- Results verification, review and approval
- Results reporting
- Investigations
- Record compilation.
- Record storage, retention and retrieval

Topics including the laboratory audit process, relevant audit documents and references, laboratory procedures, document requests by auditors, and audit training for personnel are also discussed. When self-audits of laboratory operations are completed and gaps are identified, risks are evaluated.

The remedial actions required to mitigate these risks are then prioritized and addressed.

. The auditor should investigate the following in each area and respective activities:

- Function of the specific element or activity
- Appropriate procedures are in place
- Procedures accurately reflect the practice
- Records are complete, accurate, and maintained
- Staff is compliant with procedures

## VIII.LABORATORY OVER VIEW

An overview of the laboratory operation is the first area for review in the self-audit. Areas for review in this element address the general goals and objectives, operations, function, and management of the laboratory. This type of information is requested when the auditor first arrives at the laboratory. Information regarding the type of testing conducted, qualifications of personnel and management, organizational chart, responsibilities, and other descriptive information must be readily available. Documentation and records must be provided when requested. The areas to assess here are:

- Type of testing conducted in the laboratory
- Areas and units that submit samples to the laboratory
- Organization of the laboratory, including responsibilities and accountabilities
- Qualifications of laboratory personnel
- Qualification of laboratory managemen Education, training and experience of laboratory management
- Processes which monitor laboratory performance
- Laboratory work outsourced to other areas within the company or outsourced to an outside laboratory
- Prior audit or inspection observations

## IX. INSTRUMENT MAINTENANCE AND CALIBRATION

The areas for review in this element address maintenance and calibration activities associated with instruments and other equipment. Instrument calibration is significant routine maintenance activity for analytical instruments. Instruments must be calibrated or user standardized for actual use. The following must be assessed:

- Instrument maintenance procedures
- Laboratory instrument calibration program
- Instrument calibration procedures
- Calibration records
- Instrument logbooks

## X. TEST METHOD AND SAMPLING PROCEDURE DEVELOPMENT

The areas for review in this element address the development of test methods by Analytical research and design (R&D) or other technical support functions:

- Responsibilities for the development of test methods, including sampling used in the laboratory
- Evidence that specific samples for testing are representative of the material received
- Availability of method development reports in the lab when needed for problem solving
- Transfer of methods from other labs to this laboratory
- Procedures defining test method and sampling procedure development

## XI. LABORATORY TECHNICAL TRAINING

The training of laboratory personnel and associated training records are always requested in an audit. Areas that should be reviewed include:

- The laboratory technical training program
- Process for determination of appropriate training for each analyst
- Evidence of analyst qualifications
- Retraining

Maintenance of training records and responsibility, and current records

## XII. DATA TREATMENT

The areas for review in this element address raw data recording, calculations, and other treatment of data to determine test results. The laboratory analysts who perform the analytical testing record all data, calculations, and compile instrument documentation and associated information. Calculations may be done with calculators, spreadsheets, or other computer software. If computer systems and software are involved, these must be validated. The specific areas of data treatment to be reviewed are:

- Procedures for recording data in worksheets or notebooks, labeling of instrument printouts, entry into computer systems, calculation, and result reporting
- Procedures covering averaging and significant figures
- Procedures for good recordkeeping practices (good documentation practices)
- Software and spreadsheets used to perform calculations, spreadsheet development standards, evidence of validation
- Change control

## XIII. CONCLUSION

From the beginning of engineering education, laboratories havehad a central role in the education of engineers. While there has been an ebb and flow in the perceived importance of laboratory study versus more theoretical classroom work, it has never been suggested that laboratories can be foregone completely. At times, however, they have been taken for granted to a considerable extent. The advent of the Internet, the development of powerful simulation programs enabled by enormous, cheap computing power, and the growing number of online undergraduate engineering programs have combined to refocus attention on laboratories. The fundamental objectives developed in an ABET/Sloan Foundation colloquy have helped to prompt discussion about why laboratories are important and what are the characteristics of a good laboratory exercise.

These fundamental objectives can and should provide a framework for improving current laboratory practice. Faculties who are interested in sharpening the purpose of their laboratory programs— or increasing their efficiency—can use the objectives to direct and facilitate their curricular discussions and also to judge the effectiveness of practices they observe in other institutions. The objectives can also suggest and direct research in engineering instructional laboratories by inserting a discipline that has thus far largely been absent. Instead of simply creating a clever laboratory exercise and then reporting on levels of student interest and satisfaction, researchers should be expected to identify their specific objectives and then demonstrate that those objectives have been achieved. If this standard is met, the quality and usefulness of research on laboratories will increase markedly. As a result, the community will have a greater respect for educational research and more faculty members may be able to use those activities in cases for promotion and tenure. Finally, as discussion of laboratories grows, different viewpoints are certain to emerge. The fundamental objectives can serve as a framework to sharpen and focus this discussion, whether the disagreement is about the validity of the objectives or the ways in which the objectives are met. Certainly the central purpose of engineering is still to modify nature ethically and economically for the benefit of humankind, but engineers do this increasingly from a computer terminal and not from the workshop floor or a field truck. Nonetheless, most engineering educators agree that students must have some contact—or at least be made to believe they have had contact—with nature.

Continuing discussions and further research are needed to determine the most efficient, effective way to bring this about.

Conducting self-audits on a regular basis is a good way to assess laboratory performance, improve readiness for an audit, and expose personnel to an audit experience. Using different approaches and styles as described above and in the case study is desirable. Knowledge of regulatory requirements, recommendations, and expectations as described in official documentation is mandatory.

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