# The Role of the Laboratory in Undergraduate 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. 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 along with suggestions for possible future research.**

**Keywords:** laboratories, learning objectives, history of laboratories

## 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 be 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 Instructional Laboratories

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. Seeing the impact of these efforts, other engineering disciplines joined the effort and in 1932 formed the Engineers' Council for Professional Development (ECPD), the forerunner of today's ABET (formerly the Accreditation Board for Engineering and Technology) [7].

The original ECPD accreditation criteria, published in 1933, included nine standards and filled about a half page. It was developed to offer accreditation to six disciplines: chemical, civil, electrical, mechanical, metallurgical, and mining engineering. The criteria evaluated each program using both qualitative and quantitative measures. Although students, teaching staff, graduates, curricula, institutional control and attitudes, and physical facilities were all targets for measurement, the word "laboratories" curiously did not appear. One assumes that the reason for this omission was that laboratories were so central to an engineering degree that no one could even consider teaching an engineering course without an accompanying laboratory [8]. 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. The ASEE chartered a committee to "…recommend patterns that engineering education should take in order to keep pace with the rapid developments in science and technology and to educate men who will be competent to serve the needs of and provide the leadership for the engineering profession over the next quarter century" [9]. This committee's report, called the Grinter Report after its chairman, proved to be a watershed for engineering education. Among the ten recommended action items, the first three required strengthening work in basic sciences, including mathematics, chemistry, and physics. The committee determined that the engineers being produced were too practically oriented and were not sufficiently trained to seek solutions by referring to first principles. ECPD, whose standards had gone essentially unchanged since 1933, quickly adopted these new requirements and the practical aspects of engineering generally taught in the laboratory began to give way to the more academic, theoretical subjects.

Driven by President John F. Kennedy's determination to place a man on the Moon by the end of the 1960s, there was a rapid growth during that decade in the number of students seeking an engineering degree. By the 1970s, with the Moon goal reached and the Vietnam War raging, funding for technology and for engineering education declined significantly. Major engineering projects like the supersonic transport and more advanced space missions were cancelled. Some schools reduced the number of engineering programs or shut down their engineering schools completely. To save dollars with reduced enrollments, some schools elected to minimize laboratory courses, citing the Grinter Report's conclusion that knowing theory was paramount and that engineering practicum appeared to be of secondary importance. 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 and engineering technology. This overlap of definition became problematic 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 every 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. The reports of 1967 [11], 1986 [12], and 1987 [13] reaffirmed the importance of laboratories. An Engineering Foundation conference held in 1983 attested to the importance of laboratories in engineering education and made recommendations that they be strengthened [14]. Curiously, the ASEE "Green Book" issued in 1994 [15] does not appear to mention laboratories even though there is a section on "Reshaping the Curriculum." One reasonably can assume that this reflects a satisfaction with the current situation rather than a suggestion that laboratories are of no consequence.

In the early 1990s, dissatisfaction with ABET's perceived "bean counting" approach to accreditation—that many believed rendered U.S. engineers globally uncompetitive—motivated ABET to undertake a far-reaching study on how better to accredit engineering programs. As a result, in the late 1990s ABET changed its accreditation criteria, placing the burden on each institution to develop goals and objectives for each of its programs and to develop outcomes that could be periodically assessed [16]. While the new criteria, introduced as EC2000, do not explicitly require laboratory instruction, various references to experiment, use of modern tools, and institutional support make it clear that once again laboratories are a significant part of engineering education.

During the past two or three decades, three developments have compounded the challenge of providing a quality laboratory experience for undergraduate engineers: (1) the increasing complexity—and hence increasing cost—of laboratory equipment and (2) the changing motivation of faculty members has worked against a quality laboratory experience, while (3) the integration of the computer has worked for it.

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. Objectives and Assessment (or not)

*If you don't know where you want to go, you won't know which road to take and you won't know if you have arrived.* This truism, when applied to education, suggests that clear learning objectives are essential in designing an efficient learning system and also in applying an effective system of assessment. It is surprising, however, how many teachers do not write such objectives. Some, perhaps, don't know how. Others cannot be bothered. Still others maintain that determining learning objectives should be left to the students—a position that has some merit in more advanced courses.

In the past two or three decades, several engineering education scholars have spoken to the issue of learning objectives and a number of workshops on the subject have been held. Beginning with Bloom [17], various taxonomies of learning objectives have been developed that help to explain the concept of learning objectives as well as to understand the several levels of intellectual challenge presented. It is interesting, however, that the literature is largely silent on the learning objectives associated with engineering instructional laboratories. Some professors who develop laboratories and publish their results are fairly precise in stating their objectives. Others simply assume the objectives will be taken for granted and that their contribution is to report on the laboratory apparatus, a process they have developed, or the success of their students in learning a concept or accomplishing a desired task or design.

There has been a move nationally to require educational objectives for all types of accreditation, starting with the regional accreditation commissions. For engineering, the implementation of ABET Engineering Criteria 2000 has resulted in increased attention to objectives, including some associated with the laboratory. Since the emphasis of these criteria is on objectives and assessment, work directed toward helping programs meet the criteria often focuses on those elements [18–20].

For laboratory courses, engineering faculty are much more likely to identify course goals than they are to specify student learning objectives. A common goal is to relate theory and practice or to bring the "real world" into an otherwise theoretical education [21–25]. Another goal is to provide motivation either to continue in the study of engineering or to follow a particular course of study [26–28]. In recent years, it has become apparent that fewer students come to the university with experience as "shade tree mechanics" or amateur radio operators, so laboratories are often used to give students the "look and feel" of physical systems [29] or to develop a "feel for engineering [30]."

Course goals or objectives are often stated in general terms and their achievement is not often assessed. Yet, since they are fundamental to the development of an engineer, learning objectives and their outcomes are critical for evaluating the success and evolution of a laboratory program.

There are a few examples of successful assessment of laboratory course goals. For example, student retention is something that can be measured and is sometimes used as a surrogate for motivation. The other often-used measure of success is a student satisfaction survey. As another example of assessment, the efficacy of laboratory simulations used as a prelab activity can be assessed by evaluating the performance of students when they do the physical laboratory exercise [31].

While course goals are often specified, the literature shows a general dearth of well-written student learning objectives for laboratories. Though this has not prevented the development of many innovative and effective laboratory activities, it is felt that clear learning objectives would contribute significantly to the development process as well as to the ongoing discussion about the appropriate role of laboratories in engineering education.

## IV. The Computer in the Laboratory

Today, computers are ubiquitous. An integral part of every engineer's toolbox, they are used to do computations, data collection and reduction, simulations and data acquisition, and to share information via the Internet. No engineer today could imagine doing his or her job without one. Yet, using computers routinely is a fairly recent event, particularly in the laboratory.

The first electronic digital computer, the ENIAC, became operational in 1946 at the University of Pennsylvania. Computer technology grew rapidly during the fifties and sixties with computers increasing in capability, shrinking in size, and growing in number. Still, few engineers actually used these behemoths for day-to-day design, much less to support laboratory work. In 1972 a practical breakthrough in computation occurred. Hewlett-Packard announced the HP-35 as "a fast, extremely accurate electronic slide rule" with a solid-state memory similar to that of a computer. The HP-35 and the other models that soon followed had a major impact on both theoretical courses and engineering instructional laboratories. They replaced the traditional slide rule and gave students the capability of analyzing data with far greater speed and accuracy.

The real breakthrough in computational power occurred in 1981 when IBM introduced its PC, igniting a fast growth of the personal computer market. By the mid-1980s, engineering schools were developing laboratories that made more effective use of the computer in collecting and analyzing experimental data. Bucknell, among other universities, increased the role of the personal computer in the laboratory by developing an integrated engineering workstation to support several courses. These workstations usually had a suite of electronic instruments and a PC to use in the design, analysis, and testing of engineering systems [32].

In 1993, the IEEE Education Society produced a special issue on *Computation and Computers in Electrical Engineering Education*, which represented the state of the art at the time. Papers reported successful experiments using PSPICE to model hysteresis effects, computer simulation in circuit analysis, circuit simulation in power electronics, SPICE to learn about chaotic circuits, the computer as a tool for learning stochastic processes, and so forth. The computer, clearly, was becoming integrated into undergraduate education from the classroom to the laboratory [33].

By 1986 computers were being exploited in many ways. Digital simulators were being introduced to "expand the undergraduate digital design education without increasing the student's work load" [34]. Building on several earlier efforts in finite element modeling, PCs were used to map electrostatic fields or for transmission line analysis, making difficult visualizations possible and relatively easy through interactive software [35, 36]. An example of how the PC made student learning more efficient is described in a short article by R. J. Distler:

> "Before we introduced the personal computers and emulators, the student had to assemble his program on the University's main computer and print out the resulting file. He then took this to the lab and punched the program into the ET3400 [Microprocessor Trainer], hex key at a time. If there was an error in the code, he went back to the computer terminal to correct his source code. Now the creation, of the source code, assembly, downloading, debugging, running the program and the final report preparation is done at the same station, often at a single session. Much of the frustration has been removed from running the microprocessor experiments. There has been a large increase in productivity and there has been a corresponding increase in the quality of student work" [37].

The 1980s and 1990s saw the development of many "smart" instruments that essentially married a measuring device with a special purpose computer. Connected to a system under test, the instrument collects data, analyzes it, and presents it graphically in the time it used to take to measure and record one data point. This has given students the ability to analyze much more complex systems and to do so in far greater depth.

During this period, schools began investigating the possibility of controlling experiments remotely. Early experiments saw efforts being developed around the Internet using Web browsers and Java Applets [38, 39].

One of the more comprehensive systems is LabVIEW, a product of National Instruments. This combination of software and hardware turns a personal computer into a data-acquisition device and a set of simulated instruments. It also provides software for data analysis and presentation in a variety of formats and has been used in introductory as well as more advanced laboratory courses. More significantly LabVIEW or Hewlett-Packard's HPVEE software using the HPIB IEEE 488 standard protocol instrument drivers can be used to control instruments remotely—meaning that students can not only simulate virtual outcomes of experiments, but also control real instruments while they are located elsewhere [40, 41].

Laboratory courses have also been developed to teach students to develop their own data-acquisition systems. One such course at the sophomore level uses interdisciplinary teams to design and implement computer-based systems for measuring temperature and strain and evaluating a temperature controller [42].

Clearly, the computer has changed the instructional laboratory greatly over the last few years. It can be used to control experiments; acquire data; and analyze, correlate, and present results. While this level of automation might remove students somewhat from the direct process of the laboratory experience, it can be argued that it has also extended them into areas heretofore impossible to explore. There will undoubtedly be many further developments in this area.

## V. Simulation Versus Real 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.

## VI. Hands-Off Laboratories: Distance Education

In engineering, the first distance education programs were graduate programs intended primarily, if not solely, for part-time students who were employed full time. Since most graduate programs do not include a laboratory component, the question of how to deliver laboratory experiences did not arise. As undergraduate distance learning programs started to develop, this problem demanded solution. The usual approach was to have students either perform laboratory exercises at another institution (e.g., a local community college) or spend a period of time on the engineering campus in a concentrated laboratory course [51]. In either case, the laboratory was conventional in all except the schedule of activity. Other programs gave remote students laboratory kits they could use at home to perform the course experiments. Students purchased kits at a cost considered comparable to what they would spend traveling to the campus to attend regular laboratory classes [52].

Distance education programs adopted each new technology (mail, telephone, radio, television, tape recording, computer) as it came along. None of the technologies, however, solved the difficult problem of how to provide laboratory experience at a distance. Then came the Internet, whose ability to interconnect nodes of technology in an almost instantaneous fashion changed the practice of distance education as well as the expectations of both students and teachers.

In 1996, the provost of the State University of New York convened a panel to study the development of distance education in the state and to identify areas where policy changes or clarification might be needed. The panel's report [53] provides the following apt description of the "new" world of distance education.

> "During the Panel's lifetime of less than two years, the distance learning enterprise has changed dramatically. In early 1996, most people thought of distance learning as real-time, synchronous communication that duplicated, as nearly as possible, a face-to-face classroom experience. Two years later, most realize that synchronous delivery is part of a much larger picture and that the technology and materials developed for remote delivery have a far greater potential to provide education for students 'at any time, in any place.' "

With this new understanding of "distance," the motivation for developing distance laboratories expanded significantly. In addition to the desire to provide laboratories for students who never come to the campus, there is now a wish to enhance the laboratory experience of on-campus students. There is also the potential to gain efficiencies by better utilizing space and making a single piece of laboratory equipment available to more students.

The approach most often employed is to use the Internet to provide students with remote access to physical laboratory apparatus. Most systems of this type are synchronous, giving students a sense of actual involvement in the experiment. Some use online video to further enhance students' sense of presence [54, 55]. Many systems that employ video operate in quasi real time, but others provide a capability for students to upload experiment parameters and then receive a video clip of the apparatus as it operates using those parameters [56].

The operating software for distance laboratories can be a challenge. Writing such software is a major undertaking so the use of commercial software can be efficient. Some faculty members have used MS NetMeeting [57] or MATLAB/Simulink [58] to provide access to laboratories, while others have developed their own systems [59, 60].

One concern often expressed about distance learning is the perceived isolation of the students. Hoyer et al. have used teams in Internet laboratories to provide a collaborative experience for their students [60]. Their system uses a standard browser, thereby eliminating the need for additional software on the student's computer and reducing the time required by the student to learn how to operate the system.

This perceived isolation could also cause students to disengage from the learning process, although that is less likely to occur in remote laboratory instruction than in regular class work delivered over the Internet. Having students do their laboratory work in teams, as noted above, or doing periodic self-evaluations have been effective in reducing this isolation [61].

While some educators believe that the best use of the Internet is to give students access to physical equipment in a physical laboratory, others feel that simulation by itself can provide a meaningful laboratory experience. This can range from having the students solve a problem (i.e., make a prediction) and then use a simulator to see if their solution checks "experimentally" to using a total simulation to teach students the use of electronic or mechanical instruments [62].

Since student access to an experimental apparatus is through a computer terminal, the primary question is whether a simulation can be made so realistic that the student does not know whether the other end is a software package or a set of D/A and A/D converters controlling the instruments measuring a real system. A second question is perhaps the most thought provoking: Do we need to care what the student perceives, as long as he or she meets the learning objectives associated with the laboratory? Whatever solution is used, it is apparent that the delivery of laboratory education today remains a significant challenge to distance-delivered undergraduate engineering education.

## VII. 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 laboratories 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.

The colloquy convened in San Diego, California on January 6–8, 2002. Some fifty distinguished engineering educators, representing a range of institutions and disciplines, attended.

The colloquy converged on a list of thirteen objectives, each consisting of a one-or two-word title to provide easy reference and a brief explanatory statement to help clarify the meaning. The objectives were written using the generally accepted style of using a verb to specify the action that the student should be able to perform as a result of the laboratory experience [63, 64]. The following objectives resulted from the colloquy:

*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 problem 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 the laboratory. 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 needed.

While ABET was a prime mover in initiating and developing the colloquy, ABET officials were quick to point out that the objectives have no standing as accreditation criteria. Rather, it is hoped that these objectives will be useful to pedagogues to aid in evaluating their laboratory activity and to validate their effectiveness, especially as distance-learning programs emerge. The objectives should also be useful in the design of experimental laboratory programs and in demonstrating their worthiness of extramural funding.

## VIII. Suggestions for Future Research

Engineering instructional laboratories provide a fertile field for educational research in the future. While it is always interesting and rewarding to develop new laboratory experiments and experiences, future research should be aimed at developing a more thorough understanding of this critical component of the undergraduate experience. The following are some areas that the authors and others believe can be particularly fruitful.

*1) A further understanding of the fundamental objectives of instructional laboratories:* While the ABET/Sloan colloquy produced a useful list of objectives, these need to be "calibrated" by comparison to objectives currently in use and by developing an understanding of the objectives on a disciplinary basis. Activities might include a discipline-specific survey of faculty or an analysis of proposals received by funding agencies such as the National Science Foundation.

*2) Methods of assessing laboratory effectiveness:* Starting with the fundamental objectives—or some modification thereof—it would be interesting and useful to develop and evaluate a means of assessing how well these objectives are achieved. Experts in the field of assessment could team with faculty members who are dedicated to laboratory development to design and test assessment methods keyed to the objectives.

*3) The effectiveness of remote laboratories:* As the number of undergraduate engineering distance education programs increases, it is essential that there be experimental verification that the associated laboratory experience is effective in meeting the overall objectives of the program. Ideally, this would be done by comparison with traditional offerings through evaluation of students who have completed both kinds of programs. Of course, making this kind of comparative assessment requires agreement on the objectives to be pursued and development of effective assessment methods, as noted above.

*4) Effectiveness of simulation vs. remote access of real equipment:* There is disagreement over whether or not a simulated laboratory can be as effective in meeting objectives as remote access to an experiment consisting of physical equipment. This can be explored experimentally by having students evaluate the two kinds of experiences. It would be valuable to see if a student working over the Internet can tell the difference between a physical and a simulated experiment. Students could be asked to complete the online experiment and then indicate whether they thought they were dealing with real equipment or a simulation. It will be necessary to have user interfaces that appear to be operating real equipment but are really providing access to simulations.

*5) Laboratory simulations that include "noise":* If online simulations are to represent the physical world, they must simulate not only the ideal model but the natural variability of parameters as well. Some work has been done on this, but further development would be useful. By considering the physics of the system being simulated, the developer can insert both random and systematic errors, as well as problems with instrument calibration. This added degree of "reality" could contribute significantly to the success of simulation in the context suggested in the previous paragraph.

*6) Novel approaches to meeting laboratory objectives:* At this time, many traditional experiments are not practical to perform via distance learning. Another way of approaching the problem would be not to try to find a way to perform this or that particular experiment, but rather to go back to the root of the objective and to find new experiments that meet the same objectives but that can be performed remotely.

## IX. Conclusion

From the beginning of engineering education, laboratories have had 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.


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## REFERENCES


[1] Wankat, P.C., "Analysis of the First Ten Years of the Journal of Engineering Education," *Journal of Engineering Education*, Vol. 93, No. 1, 2004, pp. 13–21.

[2] Feisel, L.D., and Peterson, G.D., "The Challenge of the Laboratory in Engineering Education," *Journal of Engineering Education*, Vol. 91, No. 4, 2002, pp. 367–368.

[3] Grayson, L.P., *The Making of an Engineer*, New York, N.Y.: John Wiley and Sons, 1993.

[4] "U.S. National Archives," Records Group 404.1 Administrative History, *www.archives.gov/research_room/federal_records_guide*.

[5] "A History of RPI," *www.eng.rpi.edu/soe/profile_history_ start.cfm*.

[6] Reynolds, T.S., *75 Years of Progress: A History of the American Institute of Chemical Engineers, 1908–1983*, New York, N.Y.: American Institute of Chemical Engineers, 1983.

[7] "Setting the Stage for a New Profession, Chemical Engineering in 1888," *www3.cems.umn.edu/orgs/aiche/archive/history/h_1888.html*.

[8] Stephan, K., "All This and Engineering Too: A History of Accreditation Requirements," *IEEE Technology and Society Magazine*, Fall 2002, pp. 8–15.

[9] Grinter, L.E., et al., "Report of the Committee on Evaluation of Engineering Education," *Engineering Education*, Vol. 45, Sept. 1955, pp. 25–60.

[10] ABET, "Criteria for Accrediting Engineering Programs 2000–2001—Conventional Criteria," 2001.

[11] "New Directions in Laboratory Instruction for Engineering Students," Report of the Commission on Engineering Education, *Journal of Engineering Education*, Vol. 58, No. 3, Nov. 1967, pp. 191–195.

[12] "The Undergraduate Engineering Laboratory," Final Report of the Quality of Engineering Education Project (QEEP), pp. 125–145, *American Society for Engineering Education*, Washington, D.C., 1986.

[13] *A National Action Agenda for Engineering Education*, Washington, D.C.: American Society for Engineering Education, 1987.

[14] *The Undergraduate Engineering Laboratory*, Edward W. Ernst, Editor, Proceedings of an Engineering Foundation Conference, July 24–29, 1983.

[15] *Engineering Education for a Changing World*, Washington, D.C.: American Society for Engineering Education, 1994.

[16] *Engineering Criteria 2000*, Baltimore, Md.: ABET, 2002.

[17] Bloom, B.S., *Taxonomy of Educational Objectives*, New York, N.Y.: Longmans, Green, 1956.

[18] Felder, R.M., and Brent, R., "Designing and Teaching Courses to Satisfy the ABET Engineering Criteria," *Journal of Engineering Education*, Vol. 92, No. 1, 2003, pp. 7–25.

[19] McGourty, J.M., Shuman, L.J., Besterfield-Sacre, M., Atman, C.J., Miller, R., Olds, B., Rogers, G., and Wolfe, H., "Preparing for ABET EC2000: Research-Based Assessment Methods and Processes," *International Journal of Engineering Education*, Vol. 18, No. 2, March/April 2002, pp. 157–167.

[20] Besterfield-Sacre, M.E., Shuman, L.J., Wolfe, H., Atman, C.J., McGourty, J., Miller, R.L., Olds, B.M., and Rogers, G.M., "Defining the Outcomes: A Framework for EC 2000," *IEEE Transactions on Engineering Education*, Vol. 43, No. 2, April 2000, pp. 100–110.

[21] Johnson, S.H., Luyben, W.L., and Talheim, D.L., "Undergraduate Interdisciplinary Controls Laboratory," *Journal of Engineering Education*, Vol. 84, No. 2, 1995, pp. 133–136.

[22] Flack, K., and Volino, R.J., "A Series-Parallel Heat Exchanger Experiment," *Journal of Engineering Education*, Vol. 88, No. 1, 1999, pp. 27–30.

[23] Bisantz, A.M., and Paquet, V.L., "Implementation and Evaluation of a Multi-course Case Study for Framing Laboratory Experiments," *Journal of Engineering Education*, Vol. 91, No. 3, 2002, pp. 299–307.

[24] Olinger, D.J., and Hermanson, J., "Integrated Thermal-Fluid Experiments in WPI's Discovery Classroom," *Journal of Engineering Education*, Vol. 91, No. 2, 2002, pp. 239–243.

[25] Okamura, A.M., Richard, C., and Cutkosky, M.R., "Feeling is Believing: Using a Force-Feedback Joystick to Teach Dynamic Systems," *Journal of Engineering Education*, Vol. 91, No. 3, 2002, pp. 345–349.

[26] Bidanda, B., and Billo, R., "On the Use of Students for Developing Engineering Laboratories," *Journal of Engineering Education*, Vol. 84, No. 2, 1995, pp. 205–213.

[27] Carlson, B., Schoch, P., Kalsher, K., and Racicot, B., "A Motivational First-Year Electronics Lab Course," *Journal of Engineering Education*, Vol. 86, No. 4, 1997, pp. 357–362.

[28] Wicker, R.B., and Quintana, R., "An Innovation-Based Fluid Mechanics Design and Fabrication Laboratory," *Journal of Engineering Education*, Vol. 89, No. 3, 2000, pp. 361–367.

[29] Leva, A., "A Hands-On Experimental Laboratory for Undergraduate Courses in Automatic Control," *IEEE Transactions on Education*, Vol. 64, No. 2, 2003, pp. 263–272.

[30] Moore, D.J., and Voltmer, D.R., "Curriculum for an Engineering Renaissance," *IEEE Transaction on Education*, Vol. 46, No. 4, 2003, pp. 452–455.

[31] Nippert, C., "Online Experiments—The Results of the Online Widener Laboratories," *32nd ASEE/IEEE Frontiers in Education Conference*, Boston Mass., November 6–9, 2002, pp. T2E-12-T2E-17.

[32] Aburdene, M.F., and El-Sharkawy, M., "Integrated Engineering Workstations in Electrical Engineering Laboratories," *IEEE Transactions on Education*, Vol. E-32, Aug. 1989, pp. 404–408.

[33] Special Issue on Computation and Computers in Electrical Engineering Education, *IEEE Transactions on Education*, Vol. E-36, Feb. 1993, pp. 1–213.

[34] Williams, R.D., "A Logic Simulator to Support Design Instruction," *IEEE Transactions on Education*, Vol. E-30, Nov. 1987, pp. 244–247.

[35] Volakis, J.L., Wang, P.K., and Harokopus, W.P., "Mapping of Electrostatic Fields Using the IBM Personal Computer," *IEEE Transactions on Education*, Vol. E-30, Nov. 1987, pp. 247–250.

[36] Chaudron, G.A., and Nachman, M., "A Computer Package for Transmission Line Analysis," *IEEE Transactions on Education*, Vol. E-30, Nov. 1987, pp. 259–262.

[37] Distler, R.J., "In-Circuit Emulators in the Microprocessor Laboratory," *IEEE Transactions on Education*, Vol. E-30, Nov. 1987, pp. 250–252.

[38] Kirkpatrick, A., and Wilson, B., "Computation and Experimentation on the Web with Application to Internal Combustion Engines," *Journal of Engineering Education*, Vol. 87, No. 5 Supplement, 1998, pp. 529–537.

[39] Shen, H., Xu, Z., Dalager, B., Kristansen, V., Shur, S. Ø, M.S., Fjeldly, T.A., Lii, J.Q., and Ytterdal, T., "Conducting Laboratory Experiments over the Internet," *IEEE Transactions on Education*, Vol. E-42, Aug. 1999, pp. 180–185.

[40] Impelluso, T., and Motoyer-Guidry, T., "Virtual Reality and Learning by Design: Tools for Integrating Mechanical Engineering Concepts," *Journal of Engineering Education*, Vol. 90, No. 4, 2001, pp. 527–534.

[41] Alexander, D.G., and Smelser, R.E., "Delivering an Engineering Laboratory Course Using the Internet, the Post Office, and a Campus Visit," *Journal of Engineering Education*, Vol. 92, No. 1, 2003, pp. 79–84.

[42] DeLyser, R.R., Quine, R.W., Rullkoter, P., and Armentrout, D., "A Sophomore Capstone Course in Measurement and Automated Data Acquisition", to be published, *IEEE Transactions on Education*.

[43] "eCircuit Center," *www.ecircuitcenter.com?SpiceTopics/Limitations.htm*.

[44] Kadlowec,J., Lockette, P.V., Constans, E., Sukumaran, B., and Cleary, D., "Visual Beams: Tools for Statics and Solid Mechanics," *32nd ASEE/IEEE Forntiers in Education Conference*, Boston Mass., November 6–9, 2002, pp. T4D-7-T4D-10, 2002.

[45] Hodge, H., Hinton, H.S., and Lightner, M., "Virtual Circuit Laboratory," *Journal of Engineering Education*, Vol. 90, No. 4, 2001, pp. 507–511.

[46] Campbell, J.O., Bourne, R.J., Mosterman, P.J., and Brodersen, J.A., "The Effectiveness of Learning Simulators in Electronic Laboratories," *Journal of Engineering Education*, Vol.91, No.1, 2002, pp. 81–87.

[47] Baher, J., "Articulate Virtual Labs in Thermodynamics Education: A Multiple Case Study," *Journal of Engineering Education*, Vol. 88, No. 4, 1999, pp. 429–434.

[48] Lee, W-J., Gu, J-C., Li, R-J., and Ditasayabutra, P., "A Physical Laboratory for Protective Relay Education," *IEEE Transactions on Education*, Vol. 45, No. 2, 2002, pp. 182–186.

[49] Svajger, J., and Valencic, V., "Discovering Electricity by Computer-Based Experiments," *IEEE Transactions on Education*, Vol. 46, No. 4, 2003, pp. 502–507.

[50] Jayakumar, S., Squires, R.G., Reklaitis, G.V., Andersen, P.K., and Dietrich, B.K., "The Purdue-Dow Styrene-utadiene Polymerization Simulation," *Journal of Engineering Education*, Vol. 84, No. 3, 1995, pp. 271–277.

[51] Bengiamin, N.Y., Johnson, A., Zidon, M., Moen, D., and Ludlow, D.K., "The Development of an Undergraduate Distance Learning Engineering Degree for Industry—A University/Industry Collaboration," *Journal of Engineering Education*, Vol. 87, No. 3, 1998, pp. 277–282.

[52] Beston, W., Private Communication, April, 2004.

[53] *Report of the University Distance Learning Panel—State University of New York*, Lyle Feisel, Chair, State University of New York, 1998.

[54] Gillett, D., Latchman, H.A., Saltzman, C., and Crisalle, O., "Hands-On Laboratory Experiments in Flexible and Distance Learning," *Journal of Engineering Education*, Vol. 90, No. 2, 2001, pp. 187–191.

[55] Kikuchi, T., Kukuda, S., Fukuzaki, A., Nagaoka, K., Tanaka, K., Kenjo, T., and Harris, D.A., "DVTS-Based Remote Laboratory Across the Pacific Over the Gigabit Network," *IEEE Transactions on Education*, Vol. 47, No. 1, 2004, pp. 26–32.

[56] Esche, S.K., Chassapis, C., Nazalewicz, J., and Hromin, D.J., "A Scalable Architecture for Remote Experimentation," *32nd ASEE/IEEE Frontiers in Education Conference*, Boston Mass., November 6–9, 2002, pp. T2E-1–T2E-6.

[57] Swamy, N., Kuljaca, O., and Lewis, F.L., "Internet-Based Educational Control Systems Lab Using NetMeeting," *IEEE Transactions on Education*, Vol. 45, No. 2, 2002, pp. 145–151.

[58] Casini, M., Prittichizzo, D., and Vicino, A., "The Automatic Control Telelab: A User-Friendly Interface for Distance Learning," *IEEE Transactions on Education*, Vol. 46, No. 2, 2003, pp. 252–257.

[59] Guimaraes, E., Maffeis, A., Pereira, J., Russo, B., Cardozo, E., Bergerman, M., and Magalhaes, M.F., "REAL: A Virtual Laboratory for Mobile Robot Experiments," *IEEE Transactions on Education*, Vol. 46, No. 1, 2003, pp. 37–42.

[60] Hoyer, H., Jochheim, A., Rohrig, C., and. Bischoff, A., "A Multiuse Virtual-Reality Environment for a Tele-Operated Laboratory," *IEEE Transactions on Education*, Vol. 47, No. 1, 2004, pp. 121–126.

[61] Sebastian, J.M., Garcia, D., and Sanchez, F.M., "Remote-Access Education Based on Image Acquisition and Processing Through the Internet," *IEEE Transactions on Education*, Vol. 46, No. 1, 2003, pp. 142–148.

[62] Huang, H-P., and Lu, C-H., "Java-Based Distance Learning Environment for Electronic Instruments," *IEEE Transactions on Education*, Vol. 46, No. 1, 2003, pp. 88–94.

[63] Feisel, L., and Peterson, G.D., "A Colloquy on Learning Objectives for Engineering Educational Laboratories," *2002 ASEE Annual Conference and Exposition*, Montreal, Ontario, Canada, June 16–19, 2002.

[64] Peterson, G.D., and Feisel, L.D., "e-Learning: The Challenge for Engineering Education," *e-Technologies in Engineering Education, A United Engineering Foundation Conference*, Davos, Switzerland, 11–16 August, 2002, http://services.bepress.com/eci/etechnologies/.

[65] Ernst, E.W., "A New Role for the Undergraduate Engineering Laboratory," *IEEE Transactions on Education*, Vol. E-26, No. 2, May 1983, pp. 49–51.

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