International Journal of Engineering Education Vol. 28, No. 1, pp. 192–201, 2012
Printed in Great Britain

0949-149X/91 $3.00+0.00

Going the Way of the Slide Rule: Can Remote Laboratories Fungibly Replace the In-Person Experience?*

EUAN D. LINDSAY
Department of Mechanical Engineering, Curtin University, Perth, Western Australia. E-mail: e.lindsay@curtin.edu.au

PHILIP C. WANKAT
School of Engineering Education, Purdue University, West Lafayette, Indiana, USA. E-mail: wankat@purdue.edu

The slide rule is an important part of the heritage of the engineering discipline, but it was ultimately replaced as the new technology of calculators overtook it. Since this scenario is potentially repeating itself now with the introduction of remote laboratory classes in engineering, it is useful to compare the current situation of hands-on versus remote laboratories with the case history of slide rule replacement by calculators. Hands-on laboratories form a core part of the education of the current generation of engineers; this paper explores whether it is possible for remote laboratories to replace them. Remote laboratories are laboratories where students conduct experiments on real, physical equipment, but the students are not physically co-located with the equipment. The key factor is the fungibility of the learning outcomes that laboratories provide—whether the remote experience can achieve all or the most important of the things that the in-person-experience can. The slide rule became obsolete because new technology could achieve the most important of its outcomes, but quicker, easier and cheaper. An analysis of remote laboratories shows that many learning outcomes are able to be achieved more easily and more cheaply in the remote mode, and additional learning outcomes are also possible, with only a small number of non-fungible outcomes preventing remote laboratories replacing the face-to-face experience.

Keywords: remote laboratory; learning outcomes; fungible; slide rule

1. Introduction

Laboratory classes are an essential part of the education of any engineering student. Among other learning outcomes they provide valuable opportunities to directly experience physical phenomena and to operate the kinds of equipment the students will need as practicing engineers. In recent years there have been an increasing number of remotely-accessible laboratory classes, where students use an internet-based telecontrol system to conduct their experiments [1]. In contrast to simulations or virtual laboratories, students actually conduct experiments with equipment in a remote laboratory. The difference between a remote laboratory and a hands-on laboratory is that students are not physically present in a remote laboratory and they cannot touch or smell the equipment, although typically they can see the equipment. The ability to conduct laboratory classes remotely offers significant flexibility advantages; however many academics have concerns regarding how well the students will learn in this access mode, and current use of remote laboratories is limited [2].

The scenario of engineering academics concerned about how a new technology is changing the teaching of their students is not a new one. There are powerful parallels between the introduction of remote laboratories and the advent of electronic calculators. Both represent threats to an element of engineering that is (or was) regarded as essential—the face-to-face laboratory experience, and the slide rule, respectively. Both represent changes in the way in which students learn, the outcomes of that learning process, and the skills that they need in order to achieve that learning.

With the benefit of hindsight, we can see that electronic calculators brought about the demise of slide rules. But is this history helpful in predicting the future? Calculators replaced slide rules; however desktops and laptops have not completely replaced mainframe computers. Just because a new technology arrives does not mean that the existing technology will disappear; instead it depends upon the functionalities offered by both.

The similarities and differences between the two scenarios offer an opportunity to enlighten the debate regarding remote laboratories. By examining how it was that calculators replaced slide rules, useful insights can be gained as to whether remote laboratories should—or indeed, can—completely or partly replace the face-to-face learning outcomes.

2. The slide rule and calculators: a case study in replacement

An important part of engineering practice is the understanding of and precise manipulation of mathematical formulae and determination of numbers from the formulae. While addition and subtraction are relatively straightforward to do by

* Accepted 20 November 2011.

hand, multiplication and division are more complicated and time-consuming, and functions such as powers and sines are even more so. In order for engineers to be able to complete such calculations quickly and efficiently, additional tools beyond pen and paper are required. For many students (identified as 'sensing' students) the determination of the numbers is critically important—the formulae are opaque to these students, but the collection and organization of numbers makes the problem real and the theory understandable [3]. Thus, the slide rule or calculator is both a calculating tool and, for many students, a learning device. This is even more evident with modern calculators that have graphing capability.

Logarithms, which were invented in 1614 by Scottish mathematician John Napier [4], convert multiplication problems into addition problems. For instance, if

$$A \times B = C$$

then

$$\log A + \log B = \log C.$$

This converts a multiplication problem into an addition problem. One way of implementing this conversion is through the use of extensive tables of logarithms, in which each of the values can be looked up. A more portable and faster option, first developed by William Oughtred in the 1620s [4] is the slide rule (Fig. 1).

By moving the two sliders relative to each other, logarithms can be added and subtracted with relative ease. Early slide rules were expensive because of the effort required to reproduce a logarithmic scale accurately; however, over time, developments in etching and manufacturing made slide rules more affordable.

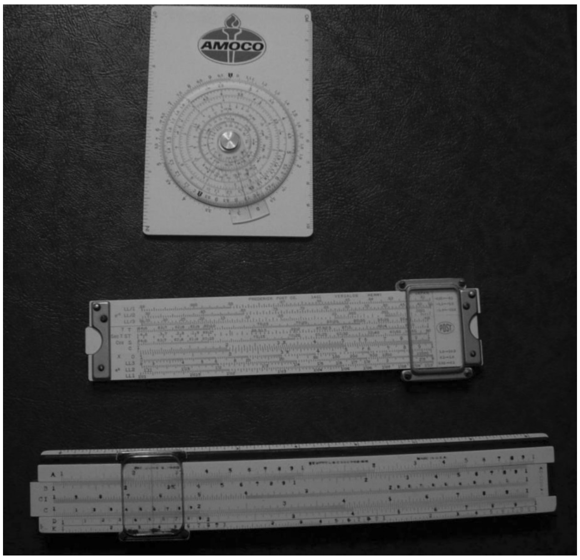

Fig. 1. Examples of slide rules. Top: Plastic Sama & Etani circular slide rule and reference tables, 1969, made in Japan, and given to author (PCW) by Amoco Oil Co. Bottom: Keuffel & Esser slide rule patented June 1900, made in USA. Middle: Post Versalog slide rule purchased by author (PCW) in 1960s, made in Japan.

The modern slide rule is credited to Amédée Mannheim who made a 10 inch rule in 1850 [4]. He included the fundamental logarithmic C and D scales for multiplication and division and the A and B scales that give x^2 compared with the C and D scales for squares/roots. More modern slide rules also included the E or LL (log–log) scale for finding powers of numbers. Slide rules might also include an S scale for sine and cosines, an L or linear scale that in conjunction with the C or D scale allowed one to determine logarithm values, a CI or reciprocal C scale that was read backwards, and a CF or folded C scale that started with π. Specialized slide rules could include a number of specialized scales.

By the 1950s, the slide rule was a quintessential part of the training of an Engineer—without a slide rule you could not be an engineer. There were a number of courses and textbooks on slide rules (e.g., [5, 6]), just as there are now courses and textbooks on calculators and computers.

Importantly, the use of a slide rule became part of the Rite of Passage into the tribe of engineers. Every engineering student carried one, often in a leather carrying case attached to his belt (there were *very* few female engineers in those days—they carried one also, but not attached to their belts.). Nowadays it is seen as the hallmark of an older engineer—a way to separate those who were trained in the 'olden days' from those who have been trained more recently. Those trained with the slide rule (including one of the authors—PCW) still believe that they are better at estimating results than those who learned entirely with calculators.

3. The technology that overcame/replaced slide rules

Computers were in use during and after the Second World War, and by the early 1960s engineering students were routinely learning to program. However, the early computers were large, not portable, and expensive. Input, originally by paper tape and then punch cards, was awkward, and programs were processed in batches that might take several hours before the output was received. There was also the ever present danger of spilling an entire box of cards; thus, requiring hours to restore the program. Thus, for routine problem solving slide rules were not displaced by computers. Mechanical calculators such as the well-known Monroe calculator were useful for addition and subtraction, but did not do division or multiplication, and they were rather bulky.

In 1972 HP introduced their portable electronic calculator that could add, subtract, divide and multiply—and that was about all. But it was more precise than the slide rule and *did not require estimation of the decimal point.* At $600 only relatively wealthy professors and students and early adopters who *had* to have the latest device bought one. This brought on a lively debate of whether it was fair to let the rich students use calculators in exams when the poorer students had to use slide rules. As competitors such as Casio and Sharp entered the market, calculators became much more powerful and less expensive. Eventually, they became cheaper than slide rules and the fairness debate, but not other negative arguments, disappeared.

The advent of calculators changed the nature of routine problem solving. Problems requiring determination of the power of numbers that had been relatively difficult on slide rules now became simple. The general speed and accuracy of students in finding numerical answers increased, although the calculator did not help in problem solving ability (if you don't know how to start a problem the method available to crank out answers is irrelevant).

By the late 1970s, it was clear to most engineers that slide rules were obsolete. Despite this, many older engineers and some engineering schools fought switching to calculators. Initially, the argument for not switching was cost and then switched to the superior ability at estimating of engineers who had been taught to use slide rules. Professors who taught a required slide rule course were slow to eliminate the course because it is human nature to argue that what one does has value. These professors argued that essential engineering skills were being eliminated. Despite these rearguard actions, calculators eventually prevailed. For example, at Purdue University the Engineering Graphics course EG 113, Slide Rules and Graphs, in the School of Civil Engineering was listed in the Purdue University Bulletin as late as 1983–85 but had disappeared from the 1985–87 Bulletin.

Ultimately, the new technology displaced slide rules because it was 'better' in a number of ways, such as:

- Calculators do not require the user to be familiar with the theory of logarithms. While it was possible to operate a slide rule without a deep knowledge of logarithms, the user at least needed to be familiar with the concept of the non-linear scale on the sliders. A calculator, however, required no additional training or knowledge—the user simply pressed the buttons that corresponded to the numbers and symbols with which they were already familiar.
- Calculators could be more accurate than slide rules. While highly accurate calculations are possible with a slide rule, the accuracy is limited by how precisely manufactured the slide rule is, and how precisely the operator can position the sliders. Higher precision calculations required a more fine-detailed scale on the slide rule, which often necessitated an increase in the size of the slide rule—giving the calculator an additional advantage with regard to portability.
- For most engineers calculators are faster, particularly for seldom-used operations such as taking powers of numbers. Of course slide rules were not made to add and subtract and calculators are clearly better for that function; however, a skilled abacus operator can often add numbers faster than a person with a calculator. The big advantage of calculators is they are fast and accurate for the average person.
- Calculators are now considerably less expensive than slide rules with the same capability. This was not originally true, but it is now an advantage of calculators.

The transition to calculators was not without loss, however. Many of the advantages of the slide rule from a usability perspective also constituted losses from a knowledge perspective, as well as other drawbacks:

- Engineers' knowledge of logarithms probably became weaker. Without the example of the slide rule that showed a useful application of logarithms, many students would be less motivated to learn these skills.
- A loss of estimation ability and weaker understanding of orders of magnitude. A very important aspect of using the slide rule was locating the decimal point. Slide rules are actually only able to multiply numbers between 1 and 10; other numbers rely upon the user to keep track of the orders of magnitude involved. The usual method for locating the decimal point was to rapidly estimate the order of magnitude of the answer. Calculators automated this process. The skill of rapidly estimating the value of calculations has never been developed by most people who were not trained with slide rules.
- Calculators require batteries. Slide rules do not.
- Slide rules are more robust—drop one and the worst that will happen is it has to be manually realigned. Drop a calculator, particularly the early models, and it may have been destroyed.
- There were also problems with the expectations of the profession. The dominant best practice was the use of the slide rule; replacing this with a

> calculator required overcoming that cultural expectation. This was a barrier initially; however, even engineers who were experts with slide rules eventually switched to calculators. Thus, calculators clearly had the advantage.

The key functionality of a simple slide rule was the ability to accurately multiply or divide numbers. More complex log–log slide rules could determine logarithms and thus find powers of numbers, and trig slide rules could determine sines, cosines and tangents. For all of these tasks the calculator was superior. It was easier and quicker to use, and the elimination of the need for knowledge of logarithms meant that there was a much wider potential audience for the technology. Ultimately, the replacement of slide rules with calculators occurred because the slide rule was replaceable in its core functions—the most valuable things that a slide rule could do were able to be done better by a calculator. Other, less valuable functionality was lost, but this was considered an acceptable price by the users of this technology. To determine whether this can also occur with laboratory classes, it is necessary to consider first their core functionality with respect to learning outcomes.

4. Engineering laboratory classes

Engineering laboratory classes were in use in the US as early as the 1870s [7]. Since then the use of laboratory work has become ubiquitous in undergraduate engineering education, to the point where it is a required part of the ABET accreditation for degree programs [8]. Criterion 3b states '*Engineering programs must demonstrate that their students attain the following outcomes: . . . (b) an ability to design and conduct experiments, as well as to analyze and interpret data*' In addition, Criterion 7, Facilities, states '*Classrooms, laboratories, and associated equipment must be adequate to safely accomplish the program objectives and provide an atmosphere conducive to learning.*' A recent book on revitalizing engineering education proposes using laboratory and design as the keys to refocus engineering education on the practice of engineering [9]. Despite this current interest in laboratories, they have not been extensively studied recently, perhaps because of a lack of consensus on the objective or outcomes expected from laboratory work [10].

One of the significant advantages of laboratory work (both remote and hands-on) is the opportunity for students to receive unexpected data—results that do not match their expectations. In this situation they are forced to examine both the data and their expectations to determine which is flawed. If the data is indeed correct, then they must change their mental model of the phenomena being explored in the laboratory—which is one of the overall learning goals of the experience.

Remote laboratories first appeared in the literature in the mid-1990s [11]. Since then they have become increasingly common, to the point where there have been reviews of the field published, e.g. [1, 12]. There are a wide variety of terms used to describe alternative access modes to laboratory classes—online labs, remote labs, virtual labs, weblabs and so forth. This range of terms covers both remote access to real equipment, as well as simulations of equipment, and it is important to be clear as to which is meant.

A remote teaching laboratory is a laboratory in which the students still control real equipment, but they do so at a distance through a technology-mediated interface, rather than in an unmediated hands-on fashion. The remote operation of equipment is common in the chemical, petroleum and nuclear industries where the operating/control room is often isolated from the equipment for safety reasons. With a remote laboratory students still have access to real equipment, and the knowledge that the results of the experiment are representative of reality, but they are not physically co-located with that equipment. The knowledge that the equipment is real is an important advantage of remote laboratories because students trust the data more than simulations while simultaneously being aware of experimental errors [13]. A typical remote laboratory implementation also differs in two other key factors. Hands-on laboratory classes are usually performed by groups of students, whereas most remote laboratory implementations are for solo access to hardware, although group instruction is certainly possible [1]. The second major difference is that hands-on laboratory classes are usually supervised by some kind of laboratory demonstrator (in the USA insurance and liability require some type of supervision), whereas most remote laboratory implementations are unsupervised.

Simulations (also known as 'virtual labs') are also a useful learning experience, allowing students to relax the constraints that reality imposes upon the learning. Different timescales can be explored; a reaction can be slowed down, sped up, or even replayed at the students' convenience. Dangerous situations can be safely explored; equipment failure (and its consequences) can be investigated. Because practicing engineers routinely use simulators, students are being trained for practice when they use commercial simulators. The advantage of a simulation, however, is also a drawback—it is not real [10]; thus, simulations are not fungible with many of the learning outcomes of hands-on and remote laboratories. Another potential drawback in simulations (and indeed in poorly constructed remote laboratories) is that the students take the 'third option'—rather than questioning their data or their expectations, they instead blame the interface [14]. Their knowledge that the data is not actually real encourages them to disbelieve its validity, and to refuse to engage in the learning process. This is a risk common to simulations; but it can be overcome with properly designed remote laboratories. Although simulations have a useful and valid role in engineering education, the remainder of this paper discusses remote laboratories conducted on real equipment, not simulations.

The combination of these factors has substantial potential to affect students' learning—indeed, there are arguments in the literature that remote and virtual laboratories are pedagogically different from the hands-on mode [15]. Despite this, however, they are becoming increasingly common because of a range of reasons. The increasing prevalence has parallels with the obsolescence of slide rules.

5. Remote laboratories: Parallels with the slide rule's obsolescence?

Slide rules were the ubiquitous standard practice up until the early to mid-1970s; it was essential that they be part of the training of every engineer. Throughout the 1970s and into the 1980s a new technology came and replaced them, because the advantages of the new technology outweighed the drawbacks.

Hands-on laboratories were the ubiquitous standard practice up until the late 1990s; it was essential that they be part of the training of every engineer. Throughout the 2000s a new technology slowly arrived with the potential to replace them—the question is whether the advantages of the new technology will outweigh the drawbacks. One difference between slide rules/calculators and hands-on/remote laboratories is that although there were different models, in effect there was only one function for scientific slide rules. Thus, calculators that could replace slide rules occurred in two steps—simple arithmetic calculators and scientific calculators. These steps were followed by calculators with more capabilities than slide rules could dream of. Laboratories, on the other hand, have a variety of different functions depending on the engineering field and the subject matter. Since experimentation is required to develop remote laboratories for the different functions and since there are different faculties involved with the different functions, we would expect a slower development and replacement process than occurred with calculators.

There are a wide range of potential advantages offered by remote laboratories, including:

- The physical separation inherent in a remote laboratory offers potential safety improvements. Some experiments are potentially dangerous to participants; the remote access mode allows these risks to be mitigated. In addition, insurance premiums may be less if students never handle the equipment.
- Remote access laboratories offer greater flexibility in scheduling. The hands-on mode requires the students, the equipment and the demonstrators to be present at the same place at the same time. Remote laboratories can be accessed at the students' convenience, often during times when a regular laboratory class could not be scheduled, such as weekends or late at night. In addition, since students from many locations can access remote laboratories they allow for more optimal use of resources [16].
- In some disciplines, remote access is a more authentic mode of instruction. Nuclear engineering facilities are controlled remotely through computer interfaces, as are large telescopes, air separation plants, and oil refineries. For students studying degrees relevant to these fields, the remote access mode may be a more transferable approach to learning to use the equipment.

For all these advantages, remote laboratories are not without their drawbacks. Primary amongst these is the perception (prejudice?) that remote laboratories are inferior to the hands-on experience—even the first remote laboratory was called 'Second Best to Being There' [11]. The objections combine two elements that were present in the obsolescence of slide rules—the cultural expectations linked to the previous technology, and the ability of the new technology to achieve the same outcomes as the old technology.

It is universally acknowledged that laboratory classes form an essential part of the training of an engineering graduate—indeed it is a necessary part of the ABET accreditation process. When it comes to documenting why laboratories are essential, there is less discussion. There have been attempts to make explicit the learning outcomes of laboratories [9, 10], but for the most part they remain implicit.

Sheppard *et al.* [9] list the following six major learning outcomes for laboratories (pp. 61–62): '*(1) learning fundamental concepts; (2) learning to use the concepts to solve practical problems; (3) learning to work with complex engineering systems; (4) learning how to communicate; (5) learning to work in teams; and (6) learning to acquire attitudes of persistence, healthy scepticism, and optimism.*' They further state (p. 62) that the laboratory is where problem solving skills are developed '*through the dynamic interaction of engineering principles, physi-*

cal evidence, and hardware.' Certainly, students learn that equipment often does not match the expectations encoded into neat theories, but ideally (p. 77) '*lab is the bridge that links the world of theory and the world of practice.*' Both of these quoted points are debatable, and many engineering professors would list design as more important for learning practical problem solving and for bridging theory and practice.

The hands-on aspects of a laboratory are a significant part of what distinguishes it from a lecture or a tutorial; it is unsurprising therefore that academics question whether a laboratory that does not include hands-on tasks can be valuable. The hands-on elements are valuable, yes—but there is a wide range of learning outcomes from a laboratory class, many of which do not depend upon the haptic interaction. In order to determine whether remote laboratories can in fact achieve most or all of the outcomes of the hands-on experience, it is necessary to consider what it is that laboratory classes are supposed to achieve and whether learning remotely can be considered equivalent to learning hands-on.

Feisel and Rosa [10] report the results of an ABET colloquia, funded by the Sloan Foundation, to develop objectives for laboratory courses in engineering, including hands-on objectives. The ABET colloquia developed the following thirteen objectives for laboratory: (1) Instrumentation; (2) Models; (3) Experiment*; (4) Data analysis; (5) Design*; (6) Learn from failure; (7) Creativity; (8) Psychomotor* (9) Safety*; (10) Communication; (11) Teamwork; (12) Ethics; and (13) Sensory awareness*. Most of these outcomes can be designed into a remote laboratory; five of the objectives (marked with asterisks) can pose problems.

6. The fungibility of learning outcomes

The essential question comes down to whether or not learning outcomes are *fungible*; that is to say can they be freely exchanged as equivalent regardless of where they are from. If one trusts the authority producing the money, money is fungible—it doesn't matter which mint your coins were produced at, they are worth the same. But when stretched, the analogy to money also leads to some of the more intricate issues in the replacement of remote laboratories. In most circumstances, money is indeed fungible, but this is not universally the case. For a coin collector looking to collect a sample of a given coin from each mint, coins are not fungible—there remains some individual significance to their history.

So it is with learning outcomes. For the most part, they may appear to be outwardly fungible, but under certain conditions they may prove themselves not to be. Constructivist theory says that the way in which learning outcomes are acquired can be as important as the outcomes themselves. While you may ultimately end up with the same understandings, how you come by them can be as important—and will ultimately change the prior knowledge for your future learning. In addition, students learn material in different ways [3], which implies that two methods may be fungible for one student and not for another.

Knowing how to plug numbers into Hooke's law is a far cry from understanding the nature of the interactions between stress and strain in elastic materials; and it is certainly not a sufficient basis for understanding plastic deformation. However if you simply wish to know how far something will stretch under a given load, it is adequate. A laboratory class on materials could cover Hooke's law to either level of depth; and different depths are differently transferable.

Calculators made slide rules obsolete by making the most valuable aspects of the slide rule fungible—the value that the slide rule provided could be found elsewhere with little loss. The learning value for many students of knowing the numbers turned out to not depend on how the numbers were generated. The argument that the one non-fungible aspect of slide rules—the ability to estimate—was valuable enough to retain slide rules did not prevail. Ultimately, the equivalence of remote and hands-on laboratories will come down to the fungibility of their learning outcomes—whether the learning can be detached from the hands-on mode and re-anchored in the remote mode. All outcomes will fall into one of three categories:

1. those that can be detached and re-anchored—the fungible outcomes;
2. those that cannot be detached and re-anchored—the non-fungible outcomes;
3. those that could never be done hands-on, but can now be done remotely—the new outcomes.

Currently, there is a clear cultural expectation that engineering students must experience live laboratory classes as part of their training. Is this a modern equivalent of the expectation that all engineering students must use a slide rule as part of their training?

The answer to this question—which this paper can hint at, but not definitively provide—depends upon whether enough of the important learning outcomes of an in-person laboratory can be unhooked from the in-person experience and re-anchored to a remote experience. Of course, an engineering degree program might decide that some laboratories should be done remotely, others could not be done remotely, and a third category can be done either way. Then the non-fungible outcomes could be clustered in the laboratories that allowed students to achieve them.

6.1 Fungible outcomes

This category covers outcomes from the laboratory class that can be achieved equally well—or indeed, better—through the remote access mode. Comparisons have been made between the learning outcomes of remote and hands-on laboratories that have shown improvements in some outcomes in the remote mode [17]. At least at some level, all of the laboratory outcomes listed by Sheppard *et a*l. [9] are fungible.

In the remote access mode, capturing of data (aka experimentation) is a fungible outcome—indeed remote instrumentation often requires more precise data acquisition techniques to allow the data to be communicated remotely.

The validation of theory is a fungible outcome. Collecting and analyzing real data that confirms a theoretical model can be achieved in either the face-to-face or remote mode. The presentation of that data may simplify or complicate the process, making the outcome easier or harder to achieve, but it remains achievable in either mode.

Webcams can provide fungible broadcast visuals (part of Feisel & Rosa's objective 13, sensory awareness) for some experiments, but not for all. If the nature of the visuals is to reinforce the results shown in the data, then fungible visuals are possible. If the visuals are required for accurate measurement (e.g., for a color change in a titration), then fungible visuals are currently not always possible. However, this is a technical issue that is likely to become less important as the technology is improved.

Communication and teamwork are important outcomes in many laboratories, particularly in the United States [9, 10]. Communication is certainly fungible between different types of laboratories and with other courses. At this time, the majority of remote laboratory implementations are solo implementations, where students complete the activities as individuals. As such the teamwork learning outcome may not be fungible with current remote laboratories, but they are fungible with other types of courses and have been designed into some remote laboratories [1, 18].

Sheppard *et al.* [9] also list learning fundamental concepts, which is certainly fungible with a wide variety of courses, and learning to solve practical problems, which is fungible with design courses and with remote laboratories. Their objective 6 'learning to acquire attitudes of persistence, healthy scepticism, and optimism' and objective 6 from Feisel and Rosa [10], 'learn from failure' are quite similar and could be designed into remote or simulation laboratories and other courses. Thus, with care in design these objectives appear to be fungible.

6.2 Non-fungible outcomes

This category includes the outcomes of face-to-face laboratories that cannot be replicated online. Many of these outcomes deal with the experience of the laboratory class, and the incidental learning gained by the students as they engage with the experiment. Five of the Feisel and Rosa objectives appear to be non-fungible, or only partly fungible, to the remote mode.

As noted earlier, most of the aspects of Feisel and Rosa outcome (3), experimentation, are fungible. This outcome also includes implementing experimental procedures that can be interpreted as a hands-on component, and this is a key non-fungible outcome. While a remote interface can change the equipment's parameters, clicking on a screen is substantially different to turning a dial. Similarly, there are categorical differences between taking readings from an analogue gauge and downloading data directly to a spreadsheet. For some equipment the direct operation is an important outcome, as it may include some important element of the operation of the equipment.

Turning a valve the right way to open it could be done remotely, but the feeling is not the same. Knowing how tightly to close a valve to stop it from leaking, but not so tightly that it is difficult to open or that threads are stripped is certainly easier to teach in a face-to-face laboratory. Of course, it is possible that turning valves, reading analogue voltmeters or pressure gauges, etc. can be taught on inexpensive equipment in a face-to-face laboratory setting, while experimentation requiring more expensive equipment could be done with remote laboratories.

Outcome (5) Design, includes 'Design, build, or assemble a part, product or system . . .testing and debugging a prototype, system or process. . . .' Building and assembling are not currently part of most remote laboratories, but they are not part of most in-person laboratories either. Although simple building and assembling (and testing and debugging) could be designed as part of a virtual laboratory, truly open-ended design is probably not possible and this part of outcome (5) does not appear to be fungible. Thus, if departments consider this outcome to be important, they need to ensure that it is addressed elsewhere in their in-person laboratories.

Outcome (8) Psychomotor is 'Demonstrate competence in selection, modification and operation of appropriate engineering tools and resources.'

Except for the strictly hands-on aspects of modification and operation, this outcome appears to be quite doable in a remote laboratory; thus, it is partially fungible.

Outcome (9) Safety is certainly an important outcome for all engineers. Although it can be taught in lecture courses and remote laboratories, it is more immediate in a hands-on laboratory. Requiring safety glasses in a hands-on laboratory makes sense, but it would be a bit silly for a remote laboratory. Thus, teaching safety and reinforcing the need for safety by repetition is probably only partly fungible. If a department chooses to use both hands-on laboratories and remote laboratories, safety can be emphasized in the hands-on laboratories.

Outcome (13) Sensory awareness was defined as 'Use the human senses to gather information and to make sound engineering judgments. . . .' Certain aspects of this outcome are not currently fungible. Engineering laboratories have a particular ambience; it is difficult to convey this environment fully at a distance. Video and audio streams are relatively straightforward; however they are constrained by the location of the cameras and microphones respectively. Haptic interfaces—elements that convey pressure feedback—are possible, but they require significant technical development to integrate into a remote operation platform. Temperature and smell are impossible at this time. The smell of burning transistors is an important rite of passage for new engineers; it is a learning outcome that is not fungible to the remote mode. Climbing a distillation column, even if only ten feet for a pilot column, is not the same as looking at a video of the column. Thus, there clearly are elements of the sensory awareness outcome that are not fungible, which again points to the advantage of having some hands-on laboratories; however, these laboratories do not require expensive equipment.

6.3 *New outcomes*

Just as there are outcomes of the face-to-face mode that are not fungible to the remote mode, there are outcomes of the remote mode that are not fungible. When considered from the perspective of a transition from face-to-face to remote, these outcomes are new outcomes that become possible in the remote mode.

One of the great advantages of remote laboratories is their inherent safety. They allow for risks present in a face-to-face laboratory to be eliminated, or for experiments that would otherwise be considered unsafe to be attempted. This allows for the inclusion of learning outcomes that would otherwise be inaccessible.

Remote access allows institutions to include experiments for equipment that is not available at the institution. This is obviously valuable for institutions in developing countries, but it is also useful for institutions in developed countries, since it allows students more flexibility in what experimental equipment to explore.

Remote access allows for much greater flexibility in the scheduling of laboratories. Students are able to schedule their laboratories at their own convenience, rather than having to conform to the institution's scheduling of resources. This allows students to attempt the laboratory when they are in their best laboratory learning mode or cannot be in the laboratory because of other duties such as paid work. Another use for remote laboratories is as a homework assignment, course project or extra credit assignment in a course that does not include an assigned laboratory. The flexibility of the remote laboratory provides opportunities that live laboratories, which need to be scheduled and supervised for insurance reasons, do not provide.

An extension of the scheduling advantage is the potential for students to engage in the laboratory in a mastery learning mode. Flexibility in the starting time of a laboratory allows the students to schedule the class to fit the rest of their lives; but flexibility in the finishing time allows the students to take as long as they need to learn the material, rather than having to leave after a fixed time regardless of their level of understanding. Alternately, if the students have to leave for other reasons, they can come back later and work on the experiment until they master it.

The online nature of the remote access mode also allows for a greater integration of the laboratory experience into a broader working environment. Students can access online resources (such as external websites) while in the laboratory. Students can easily write up their reports as the laboratory progresses, capturing data electronically and inserting it directly into a document. This integrated work environment becomes possible in the remote mode; proficiency in such environments thus becomes an achievable goal.

One inherently new learning outcome is familiarity with remote operation of equipment. Controlling equipment remotely is an increasingly common task for engineers; familiarity with these operations is an increasingly valuable learning outcome for graduates. Familiarity with remote laboratories is also valuable for students who engage in multiple different remote experiments. Consistent interfaces across multiple remote laboratories can allow quicker familiarization for students, making it easier for them to engage in new laboratory classes. On the other hand, use of different interfaces will familiarize the students with different tools. It is difficult to make a definitive judgment regarding the relative value of each of these learning outcomes—different learning experiences will place a different emphasis upon each of the outcomes, and the list is far from exhaustive.

7. Resources

Ultimately, remote laboratories will only be adopted if the necessary resources are made available. Unlike the shift from slide rules to calculators, where the decision is made by the individual student, it is the universities that decide whether to adopt remote laboratories.

There are some key financial incentives towards adopting remote laboratories. The non-supervised nature of most remote laboratory classes means that demonstrators are no longer required. This is an attractive feature when it comes to reducing the overall expense of offering laboratory classes to students. A demonstrator or teaching assistant will need to do some equipment set-up such as stock chemicals, but these operations do not take long and can be done ahead of time.

A more compelling argument, however, is the potential increased return on investment for laboratory expenditure. Investing in face-to-face laboratory equipment provides only your students with access to only the equipment you purchase. Remote laboratories allow institutions to purchase access to equipment, rather than the equipment itself. This is a particularly attractive option in developing countries where equipment funds are scarce [19] . Conversely, remote laboratories allow expensive equipment to be much more fully utilized [16], with access to under-utilized equipment able to be traded for access to equipment only available elsewhere. Agreements between institutions to share remote laboratories are emerging, both at the individual level [20] and at the institutional consortium level [21].

8. Conclusions

An analysis of the goals of laboratory education shows that not all of the learning outcomes are fungible with regard to mode. Some outcomes are achieved better in the remote mode; some can only be achieved in a face-to-face implementation. While it is possible to achieve broadly the same outcomes, to achieve an exact substitution is impossible. This was also the case for the slide rule. Not everything that can be done on a slide rule can be done on a calculator; also, there are opportunities that calculators, particularly the newer ones with memory, programming and graphics, provide that slide rules do not.

What governs the evolution is the relative value of these functionalities. If the new unique outcomes are more valuable than the non-fungible outcomes, and the fungible outcomes can be achieved equally well, then the new technology will prevail. For the slide rule, the new outcomes of speed, convenience and accuracy outweighed the loss of estimation ability for almost all engineers.

This agreement in the relative value of outcomes is what promoted the transition to the new technology, and it also serves as a barrier to the transition to remote laboratories. For universities, flexible and efficient delivery of their laboratory classes is a valuable new outcome. For industry, knowledge and experience with remote control of equipment is a valuable new outcome.

As remote control of equipment becomes a more and more common industrial practice, the value of the new outcome of controlling remote equipment will increase, the perceived value balance will shift to the new technology, and remote laboratories will gain more acceptance. The question will be whether the non-fungible outcomes will be lost in the transition. If some laboratory courses become remote laboratories and others remain in-person laboratories, universities may be able to retain all current outcomes, obtain some additional outcomes, increase flexibility for students, and reduce costs.

References

1. C. Gravier, J. Fayolle, B. Bayard, M. Ates and J. Lardon, State of the art about remote laboratories paradigms—foundations of ongoing mutations, *International Journal of Online Engineering,* **4**, 2008, pp. 19–25.
2. A. K. M. Azad, Internet accessible remote experimentation: Setting the right course of action, *International Journal of Online Engineering,* **6**, 2010, pp. 4–12.
3. R. M. Felder and L. K. Silverman, Learning and teaching styles in engineering education, *Engineering Education,* **78**, 1988, pp. 674–681.
4. J. E. Thompson, *The Standard Manual of the Slide Rule: Its History, Principle and Operation*, D van Nostrand Company, Princeton, NJ, 1952.
5. E. I. Feisenheiser, *Versalog Slide Rule Instructions*, Frederick Post Co., 1963.
6. C. C. Bishop, *The Slide Rule and How to Use It*, Barnes and Noble, 1955.
7. L. P. Grayson, *The Making of an Engineer*, Wiley, New York, 1993.
8. ABET, Criteria for Accrediting Engineering Programs, Effective for evaluations during the 2010–2011 accreditation cycle, 2010.
9. S. D. Sheppard, K. Macatangay, A. Colby and W. M. Sullivan, *Educating Engineers: Designing for the Future of the Field*, The Carnegie Foundation for the Advancement of Teaching, San Francisco and Jossey-Bass, 2009.
10. L. D. Feisel and A. J. Rosa, The role of the laboratory in undergraduate engineering education, *Journal of Engineering Education,* **94**(January), 2005, pp. 121–130.
11. B. Aktan, C. A. Bohus, L. A. Crowl and M. H. Shor, distance learning applied to control engineering laboratories, *IEEE Transactions on Education,* **39**(August), 1996, pp. 320–326.
12. J. Ma and J. V. Nickerson, Hands-on, simulated, and remote laboratories: A comparative literature review, *ACM Computing Surveys,* **38**(September), 2006.

13. K. Jona, R. Roque, J. Skolnik, D. Uttal and D. Rapp, Are remote labs worth the cost? Insights from a student of student perceptions of remote labs, *International Journal of Online Engineering,* **7**, 2010, pp. 48–53.
14. E. D. Lindsay, S. Murray, D. Liu, D. B. Lowe and C. G. Bright, Establishment reality vs. maintenance reality: how real is real enough?, *European Journal of Engineering Education,* **34**, 2009, pp. 229–234.
15. E. D. Lindsay, S. Naidu and M. Good, A different kind of difference: Theoretical implications of using technology to overcome separation in remote laboratories, *International Journal of Engineering Education,* **23**, 2007, pp. 772–779.
16. M. Stefanovic, M. Matijevic and V. Cvijetkovic, Web-based laboratories for distance learning, *International Journal of Engineering Education,* **25**, 2009, pp. 1005–1012.
17. E. D. Lindsay and M. C. Good, Effects of laboratory access modes upon learning outcomes, *IEEE Transactions on Education,* **48**, 2005, pp. 619–631.
18. M. G. Helander and M. R. Emami, Engineering eLaboratories: Integration of remote access and eCollaboration, *International Journal of Engineering Education,* **24**, 2008, pp. 466–479.
19. I. M. Michaelides and P. C. Eleftheriou, Using engineering remote laboratories to enhance student learning—a distributed experience, *International Journal of Engineering Education,* **25**, 2009, pp. 577–584.
20. J. Henry and D. DiBiasio, Personal communication to P. C. Wankat, 2010.
21. D. B. Lowe, S. Conlon, S. Murray, L. Weber, M. de la Villefromoy, E. D. Lindsay, A. Nafalski, W. Nageswaran and T. Tang, Labshare: towards cross-institutional laboratory sharing, *Internet Accessible Remote Laboratories: Scalable E-learning Tools for Engineering and Science Disciplines*, A. K. M. Azad, M. E. Auer and J. Harward (eds), IGI Global, 2011.

Euan Lindsay is a Mechatronic engineer, a discipline that integrates computers, electronics and physical hardware. Dr Lindsay's Ph.D. investigated whether remote and simulated access alternatives to the traditional in-person laboratory experience could provide the same learning outcomes for students. Dr Lindsay's work in Remote and Virtual laboratory classes has shown that there are significant differences not only in students' learning outcomes but also in their perceptions of these outcomes, when they are exposed to the different access modes. These differences have powerful implications for the design of remote and virtual laboratory classes in the future, and also provide an opportunity to match alternative access modes to the intended learning outcomes that they enhance.

Dr Lindsay is an Associate Professor in Mechatronic Engineering at Curtin University, in Perth, Western Australia. His research interests include engineering education, telecontrol (particularly internet-based telecontrol), artificial neural networks, and rehabilitative technologies for people with sensing impairments.

Dr Lindsay was the 2010 President of the Australasian Association for Engineering Education, and co-edits the *Australasian Journal of Engineering Education*. He is a Fellow of the UK Higher Education Academy. Dr Lindsay was the recipient of a 2007 Carrick Award for Australian University Teaching. In 2005 he was named as one of the thirty Most Inspirational Young Engineers in Australia.

Phillip Wankat was initially trained to use slide rules and punch cards. He is currently the Clifton L Lovell Distinguished Professor of Chemical Engineering. His research interests include simulations of new separation methods and engineering education. He is the co-author of *Teaching Engineering*, available free as pdf files on the web at https://engineering.purdue.edu/ChE/AboutUs/Publications/TeachingEng/index.html, and he is the author of *The Effective Efficient Professor: Teaching, Scholarship and Service*, Allyn & Bacon, 2002. His textbook *Separation Process Engineering,* 3rd edn, Prentice-Hall, 2012, contains a significant number of detailed simulation exercises.