

# Elements of a Realistic Virtual Laboratory Experience in Materials Science: Development and Evaluation\*

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*The development and evaluation of a realistic virtual materials science laboratory experiment on metallography is reported in this paper. This virtual laboratory is highly interactive and has been designed considering a number of learning styles. All standard laboratory functions such as stating the objectives of the experiment, background, procedure, analysis, and establishing conclusions are performed in a virtual environment. A novel 'decision tree' structure is devised that allows the user to make decisions from an available menu of options (both correct and incorrect options are given) and view the results of the decision. The students can view the outcome of an incorrect decision using the decision tree concept. The objectives of this tool are to 1) emphasize and verify the learning objectives, 2) prepare the students for an actual in-class laboratory experiment, and 3) serve as a replacement experience for universities and colleges that do not have a materials science laboratory. Preliminary evaluation of the software by students has shown that the software can be effective in achieving the learning objectives and in serving as a preparation tool for laboratory students. An interactive version of this paper is available on the IJEE website ([www.ijee.dit.ie](http://www.ijee.dit.ie)).*

## INTRODUCTION

THE LABORATORY experience represents one of the few hands-on experiences in engineering education. This experience serves to reinforce theoretical concepts discussed in engineering courses and provides an experiential learning process. In order to have an effective laboratory experience, extensive personnel time must be used to assure a well-organized experience with detailed procedures, and updated equipment. Often, even after extensive investment of time and resources by the university, the actual student experiences in these laboratory courses may not be positive ones.

Generally, students express that some of the deficiencies of a laboratory experience are related to:

- lack of familiarity with the procedure;
- equipment;
- measurement tools and methods;
- calculation techniques.

Interactive software could potentially address some of the deficiencies enumerated above and improve the students learning experience and performance.

With recent advances in multimedia technologies, the computer-based delivery mode is making

progress and it has become possible to design educational software that teaches a subject in an interactive fashion [1]. Software has the ability to provide immediate feedback to the user as to the correctness of the approach and/or the solution. Although computer assisted instruction (CAI) is seemingly having an impact on undergraduate science, mathematics, engineering, and technology education, it has yet to become a significant force in laboratory instruction. We suggest that a computer-based tool that allows the student to step into the experiment, follow a procedure, complete the experiment, collect and analyze data, and assess his or her findings, allows a student-oriented learning process to take place that can significantly improve the learning experience as compared to traditional laboratory approaches. This tool can decrease the reliance of the students on the instructor and allow the instructor to contribute in a more meaningful way to the learning process. Allowing interaction with the software is critical in order to avoid a purely demonstration experience and promote self-guided and student-empowered learning [2].

Development of virtual laboratories is not a novel idea. Elsherbeni *et al.*, developed one of the early virtual laboratories in microwave and electronics as purely a visualization tool [3]. Some of the earlier efforts in the development of such tools in various engineering fields are those by Chevalier

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*et al.*, in the mechanics area [4], Monter-Hernandez *et al.*, in power electronics [5], Avouris *et al.*, in computer-assisted laboratory courses [6], and Wyatt *et al.*, in geotechnical topics [7]. Some of the more interactive efforts are those reported by Bhandari and Shor in the area of controls [8], Budhu in soil mechanics [9], and Schmid in controls [10]. There is a tremendous amount of virtual laboratory software on various subjects available in the literature and on Internet sites. Some subject areas are more adaptable to these approaches such as controls, power, circuits, mathematics, and physics compared to other areas that require more visualization and programming such as equipment-intensive laboratories in which the procedures are crucial and complex.

In the specific area of materials science and engineering, there exists commercially available software that serves to enhance the learning experience of the students in this area [11]. The software is an excellent concept visualization and enhancement tool, but it is not a virtual laboratory. Another effort in the direction of multi-media virtual laboratories in the area of mechanics and materials science was recently reported [12]. The authors have developed, as part of an integrated mechanics and materials course, a virtual laboratory module on tensile testing which is an important concept and experience in all engineering programs. The software is interactive, allows for student participation, and is designed based on learning theories proposed by Russ on motivation to learn through software presentation [13].

In this paper, we present the development process and the necessary elements of an interactive virtual materials science laboratory module. The novelty of the approach is in its focus on laboratory procedures as a preparation tool for an actual experiment in materials science. New features are incorporated into the software that allow the student to make decisions, observe the results of the decision (both correct and incorrect outcomes are provided), and find the correct path through a trial and error process, as is the case in an actual laboratory environment. The software is designed based on conventional and more recent learning theories and it also accommodates various learning styles. This software can serve as a preparation tool for an existing materials science laboratory course or as a replacement tool in organizations where a materials science laboratory experience does not exist.

## METHOD

The development approach takes advantage of the existing software technology (Macromedia's Authorware and Flash), multimedia technology (digital video, still photography, sound), and a logical and structured approach to the presentation of materials [14]. A flow chart, developed as a blue print of steps taken in the experiment, is used

to emphasize important concepts in the experiment, identify junctions that require visual or audio reinforcements, identify potential crossroads, and determine what needs to be measured, calculated, and reported. The authors also carefully constructed menu options to maximize the intuitive flow of the interface for the student [15].

As with the design and preparation of any educational tool, the design of educational software must consider both conventional and modern learning theories. For example, according to conventional theories, subjects learn through cognitive and experiential means [16]. Rogers states that experiential learning can be applied to the solution of one or more specific problems (for instance what engineers learn) and is important for long term retention and deeper learning. To achieve experiential learning, the teacher, or in our case the software, must accommodate the learner's involvement and self-evaluation, without dominating the process [16].

More modern theories specifically related to software design state that learning should be designed around a situation or an 'anchor' using a case study or a problem situation [17], i.e. 'anchored instruction'. Interactive multimedia tools can easily achieve this but should allow for exploration by the user. Perhaps the strongest influence in the design of the structure of this software has been the conditions of learning proposed by Gagne [18]. Gagne suggests that, when designing instruction, various instructional events must be accommodated for learning to occur. These include gaining attention, presenting the objectives, requiring recall of learned subjects, presenting stimulus, guidance, feedback, requiring performance, assessing performance, and enhancing retention.

In addition to the importance of learning theories, in designing software, one must consider that styles of learning also play an important role in education and teaching [19]. While the empirical evidence for the predictive validity of student learning style in terms of academic performance is convoluted, Sternberg and Grigorenko indicate that clearly learning preferences do exist and impact student motivation and satisfaction in a learning environment [20]. As an example, McCarthy asserts that there are four different learning styles: innovative (need reason for learning—why do I need this?), analytic (want to deepen their understanding—learn effectively from lectures), common sense (want to know how things work—learn it and try it), and dynamic (want to learn on their own—*independent learners*). Regardless of the particular learning styles instrument or theoretical approach you select, effective pedagogy must consider the learning style of the audience, and the learning tool must address and attempt to accommodate a variety of learner preferences. Instructional materials that present material in multiple modalities are more likely to engage and maintain student attention

[21]. Materials that are designed with learner preferences and limitations are more likely to create an environment conducive for learning [22].

The virtual experiment presented here is based on a 'Metallography' experiment, which is performed in any materials science laboratory course. Metallography is the process of preparing and analyzing the internal microstructure of metallic specimens through optical techniques. The experiment requires up-dated equipment and facilities such as grinding wheels, polishing wheels, specimen mounting kits, and a metallograph (a metallurgical microscope). The following is a synopsis of the important elements used in the development of the software.

#### *Objective of the experiment*

In our metallography module, the student is given an initial brief introduction as to the objectives of the experiment i.e. what is metallography and what it is used for. For example, the metallography is used for inspecting failed components to determine where, why, and how this failure occurred. The authors consider this as the anchor of the experience. This positively influences the innovative learners who need extrinsic and application-oriented reasons for learning.

#### *Brief introduction of the metal*

The students can then choose from a menu of metal choices and begin the experiment. For every chosen metal, a brief background is given describing the structure, important features, and applications of the metal, Fig. 1. Once the short introduction stage is completed, the experimental procedure begins.

## PROCEDURE

The procedure is presented in a step-by-step methodical fashion. Where needed, a video-clip of the actual process such as specimen mounting, releasing, grinding, polishing, and etching are given. For instance, the user selects the first stage of the process, which is specimen mounting and preparation. Here, the student is shown a short, but detailed, clip of a metal sample being mounted, and the sample being prepared. The stages that follow, including sample grinding (makes the surface uniform), polishing, Fig. 2, (makes the surface smooth), and etching, (the surface is exposed to a chemical), are presented in the same manner with a reasonable degree of detail.

Analytic and common sense learners who want to deepen their understanding and learn how things work are targeted in this section. For example, the progressive improvement in the surface of the metal after the completion of the grinding and polishing processes is verified by providing high and low magnification images of the surface, Fig. 3. This is practically impossible to do in an actual laboratory environment.

#### *Decision tree*

A 'decision tree' structure that allows the student to make a decision from a menu of options about a certain step in the experiment is incorporated into the software [24]. The purpose of this feature is to engage the dynamic independent learner. Consider the etching process: one major element of the etching process is the selection of the time period that the surface must be exposed to the chemical of choice. This time generally varies from sample to sample and the students, in an actual laboratory experience, go through a trial

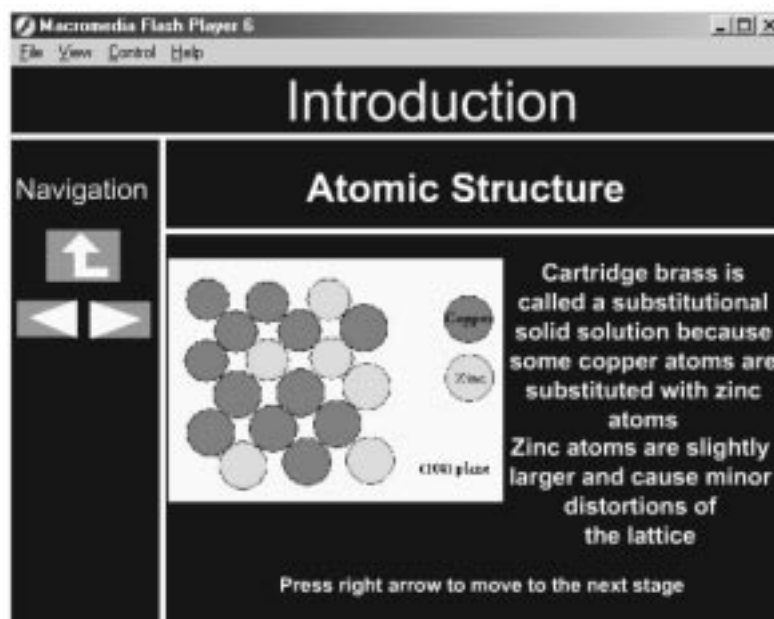


Fig. 1. Introduction and objectives of the experiment.

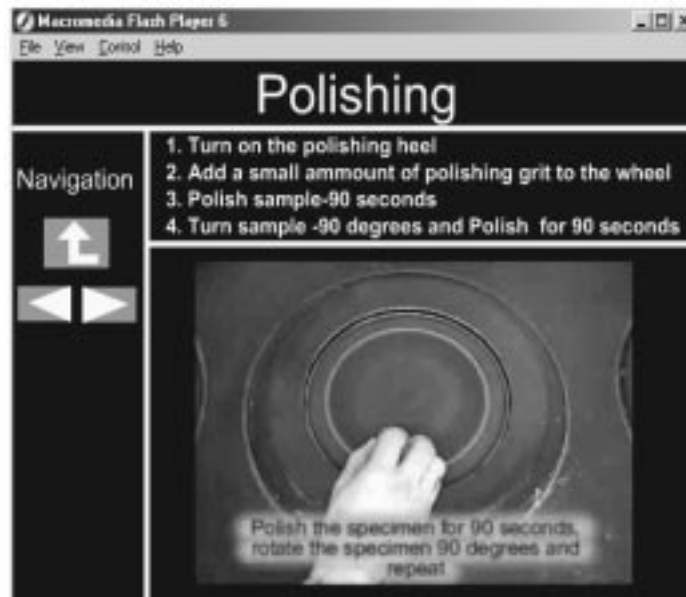


Fig. 2. The virtual lab showing various preparation stages of the sample.

and error process to find the most effective etching time. In doing so, they find out what happens if they use an excessive or an insufficient period of etching time.

The same process is integrated in the software as a decision tree, Fig. 4. The decision tree asks about the proper etching time for a brass sample and four options are given ranging from ten to ninety seconds. Clearly, the student may not have any idea about the proper etching time but they can guess and go through a trial and error process. For example, if the user selects ninety seconds (an incorrect answer) as the proper etching time, a photomicrograph of the sample will be shown at a specific magnification after ninety seconds of exposure time. On the same page, the student is asked if the surface is properly etched (two options

are given: Yes or No). If the user responds 'Yes', the software prompts the user with an incorrect decision and also explains why the given etching time is incorrect. In this case the user is given an explanation that the exposure time is too long and therefore the features are overwhelmed by the extensive chemical reaction and the sample is 'over-etched'. At this point the user is prompted to try again and choose another etching time. If the user selects, for example, ten seconds as the etching time (an incorrect answer), the same exact process is repeated and the user learns what happens to a sample if it is exposed to an etchant for short periods of time, i.e. the sample is 'under-etched'. The process is repeated until the student makes the correct decision and selects a proper etching time. In going through this process, the user makes

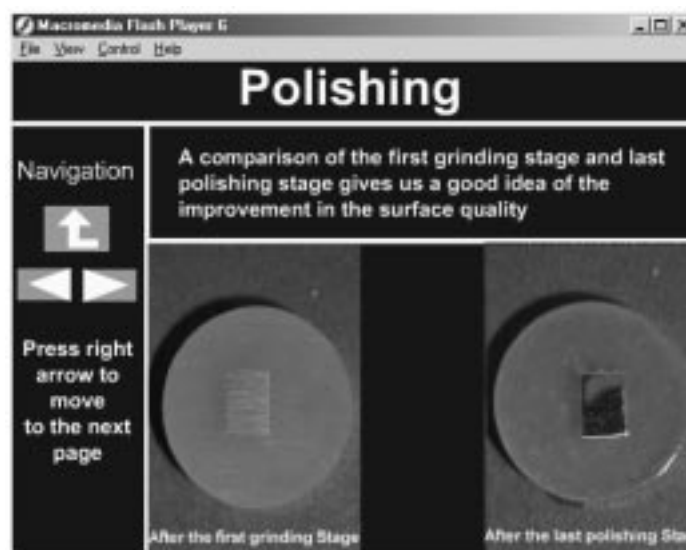


Fig. 3. Images showing the surface quality after the polishing process.

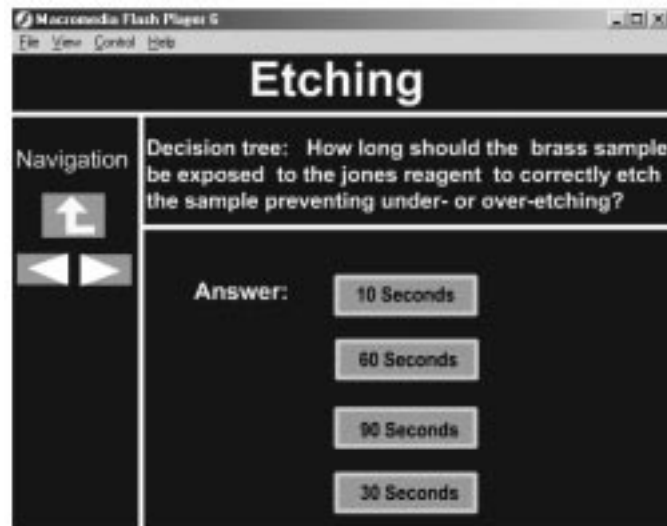


Fig. 4. The 'decision tree' structure.

decisions, observes the results of his or her decisions, and learns important concepts with both the correct and incorrect answers. This aspect of the software illustrates and promotes an experiential learning process.

After the etching stage is completed, students can observe the microstructure at various magnifications as presented by the software, Fig. 5. Important information is given about various features that they observe in each photomicrograph. This is done through the simulation feature of the virtual laboratory. Various microstructural features are observed and presented at a specific magnification using a digital video simulation.

#### *Measurements and calculations*

After basic observations of the microstructural features, the students are presented with a

step-by-step procedure of calculating the ASTM grain size number for the metal. For example in determining the ASTM grain size of a brass sample, Fig. 6, the students are first presented with the procedure of determining the grain size which includes: taking a photomicrograph at a specific magnification, counting the grains on the boundary of the photomicrograph (counted as half grains), counting the grains on the inside of the micrograph (full grains), modifying the counted total grains for the magnification of interest, and finally the determination of the grain size number. All steps are presented through digital simulation clips allowing a dynamic process of learning and visualization.

A similar process is developed for the calculation of average grain diameter. Each step in the process is explained in detail and the students are

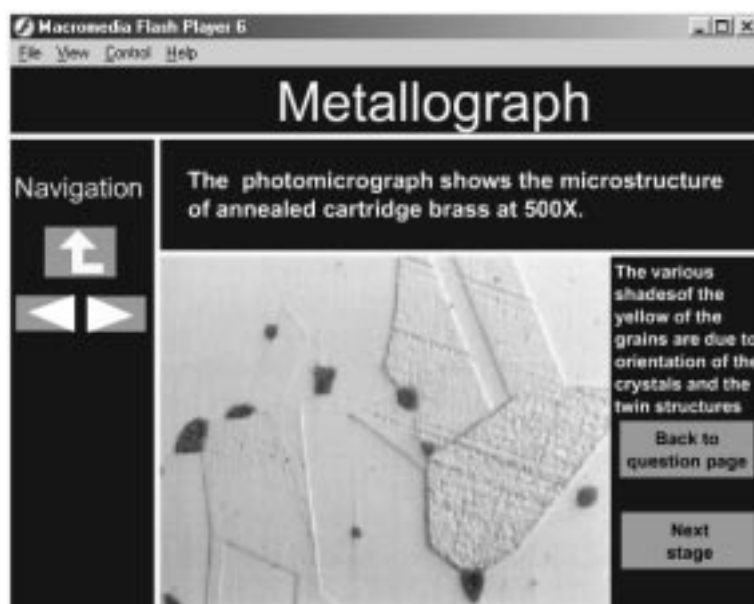


Fig. 5. Examining the microstructure at higher magnifications and identifying the microconstituents.

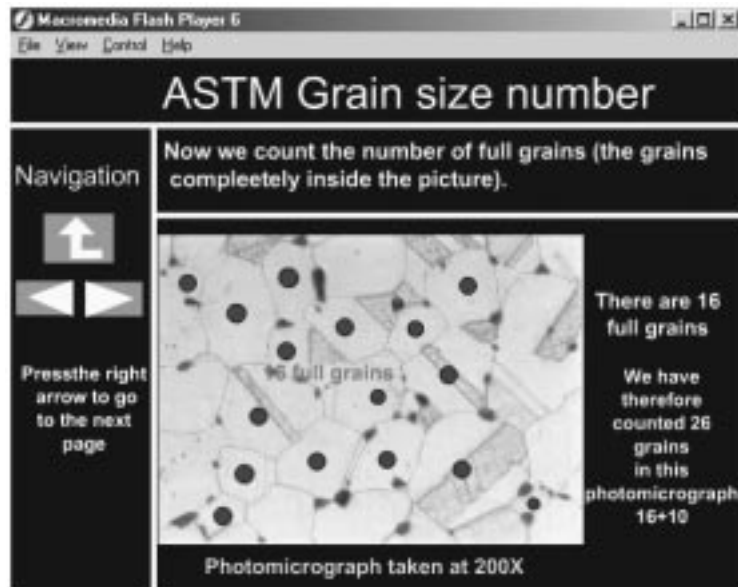


Fig. 6. The ASTM grain size determination.

guided through the important details of making measurements and performing calculations. The student will then be directed to the metal menu page to select another metal.

#### *Requiring 'recall'*

In going through the microstructural analysis of the second metal, the previous grinding, polishing, and etching information is not repeated. Instead the students are asked questions that test and verify knowledge gained during the previous round. For example, when discussing grinding, the students are asked questions, Fig. 7: How many stages of grinding are necessary? What is the progression of the grit size during grinding operation? What is the average grain diameter of the sample shown? These issues were discussed in detail during analysis of the first metal, and here instead of repeating them, we require 'recall' to

assure that the student has learned the topic. The students are not given any help or explanation in this stage but with every wrong answer a helpful hint is given to direct them to the correct answer.

#### SOFTWARE EVALUATION

The developed software was evaluated in two forms:

1. An evaluation was performed to determine if the software can achieve its learning objectives in a standard lecture course.
2. A usability study was performed to determine if the students enrolled in the actual laboratory course would find the presentation and the contents of the software beneficial to their performance, learning, and understanding in the laboratory course.

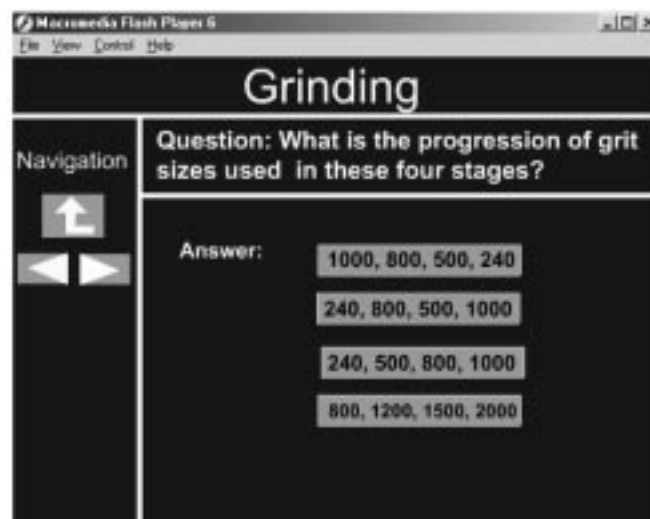


Fig. 7. Questions requiring recall.

### Non-laboratory students

The developed module was evaluated by two groups of advanced undergraduate students (58 junior level students) that had not taken the materials laboratory course and had no knowledge of the procedure and objectives of the virtual experiment. These students were enrolled in Mechanics of Solids and Materials Science courses. The students in the materials science class had exposure to some of the learning objectives presented in the software. Access to the software was provided to the students through the Internet. The students were asked to review the virtual experiment and at the conclusion of the experiment they were asked to take a quiz consisting of twenty-two questions. The questions were designed to test student understanding of the experiment objectives (2 questions), learning objectives (11 questions), procedure (7 questions), and calculations (2 questions). The performance average of the students who took the quiz was calculated to be 80.1 with a standard deviation of 9.7.

Approximately, three weeks after the students were exposed to the virtual laboratory, the students were asked to evaluate the software in various areas including ease of navigation, flexibility, screen elements, feedback elements, and the overall learning experience, Table 1. The range of the response for each statement or question was set from '1' (very negative) to '9' (very positive). The first group of questions (Q # 1–6) were given to determine the level of student sophistication and involvement with Internet, software, and other computer experiences. The responses show that this group of students had extensive experience with spreadsheet ( $\mu = 5.43$ ) and in general software use ( $\mu = 6.25$ ). The second group of questions (Q # 7–12) related to general reaction to the overall experience. The purpose here was to assess the student attitude toward this specific software as far as the overall experience, ease of use, flexibility in navigation, and learning objectives. The response was not overly enthusiastic but was not disappointing either. In general the students found the experience to be a positive one, relatively easy and flexible, and the most important issue was that they believed that they learned from the software ( $\mu = 6.29$ ). The results here hint at the fact that there is resistance on the part of students toward using software as a learning tool.

We also asked questions about the screen elements and the general layout of the software (Q # 13–16). The results were very encouraging and the students revealed very positive view of the way the software was designed with the use of icons ( $\mu = 6.91$ ), characters ( $\mu = 6.82$ ), imagery ( $\mu = 6.81$ ), and layout ( $\mu = 6.46$ ). The navigation through the software was also evaluated (Q # 17–23) and this also showed very positive student view of the software. The impromptu quizzes spread throughout the module were very popular ( $\mu = 6.82$ ). The quizzes add more interactivity to the software and the students like that.

Table 1. Descriptive statistics

Q#	Category	Number of Responses	Mean	Std. Deviation
<b>Computer Experience</b>				
1	Word Processing	58	6.2586	2.22868
2	Spreadsheet	58	5.431	2.42148
3	Database	57	3.1579	2.16126
4	Graphic Program	58	4.5517	2.33338
5	HTML Editor	58	2.1034	1.92572
6	Games	58	5.8793	2.78516
<b>Reaction to the Virtual Laboratory Experience</b>				
7	Wonderful	58	5.9138	1.64674
8	Satisfying	58	5.5345	1.5584
9	Stimulating	58	4.9138	1.91288
10	Easy	58	5.9655	1.54427
11	Flexible	58	5.2759	1.38657
12	Learned	58	6.2931	1.55607
<b>Screen Elements</b>				
13	Characters	58	6.8276	1.5118
14	Icons	58	6.9138	1.36734
15	Layout	58	6.4655	1.41688
16	Slides	58	6.8103	1.43217
<b>Ease of Navigation</b>				
17	Navigation	58	6.5345	1.72917
18	Movies	58	6.4483	1.63484
19	Quizzes	58	6.8276	1.82707
20	Move Lab	58	6.569	1.79778
<b>Module Helpfulness</b>				
21	Feedback	58	6.431	1.78799
22	Movie Clips	58	6.1034	1.96183
23	Text	58	6.6552	1.34493
<b>Course Module Design</b>				
24	Helpful	56	6.7679	1.12801
25	Help Understand	56	7.0179	1.21343
26	Helped learn	56	6.5714	1.3329

In determining which aspects of the module were really helpful to the students, instant feed back ( $\mu = 6.4$ ), movie clips ( $\mu = 6.1$ ), and text materials ( $\mu = 6.6$ ) all showed strong influence. Questions were asked to determine if such software would be helpful as a learning tool to accompany lecture or a laboratory course (Q # 24–26). The responses were very positive in this category of questions showing that the software was helpful ( $\mu = 6.76$ ), helped them understand the objectives ( $\mu = 7.01$ ), and helped them learn ( $\mu = 6.5$ ).

### Laboratory students

The authors conducted usability studies on the virtual experiment on metallography. Schneiderman indicates that a critical cog in usability testing is generating an end user survey to complete after the interface task [24]. Another key element of user-directed interface design is involving the target users in evaluating the interface [25]. As such, students enrolled in the Materials Science Laboratory reviewed the software either prior to the actual lab experiment (19 students) or after completing the actual lab experiment (14 students). Each student completed a survey based on five general areas of evaluation: overall impression (6 questions); screen elements (4 questions); navigational structure (4 questions); course module

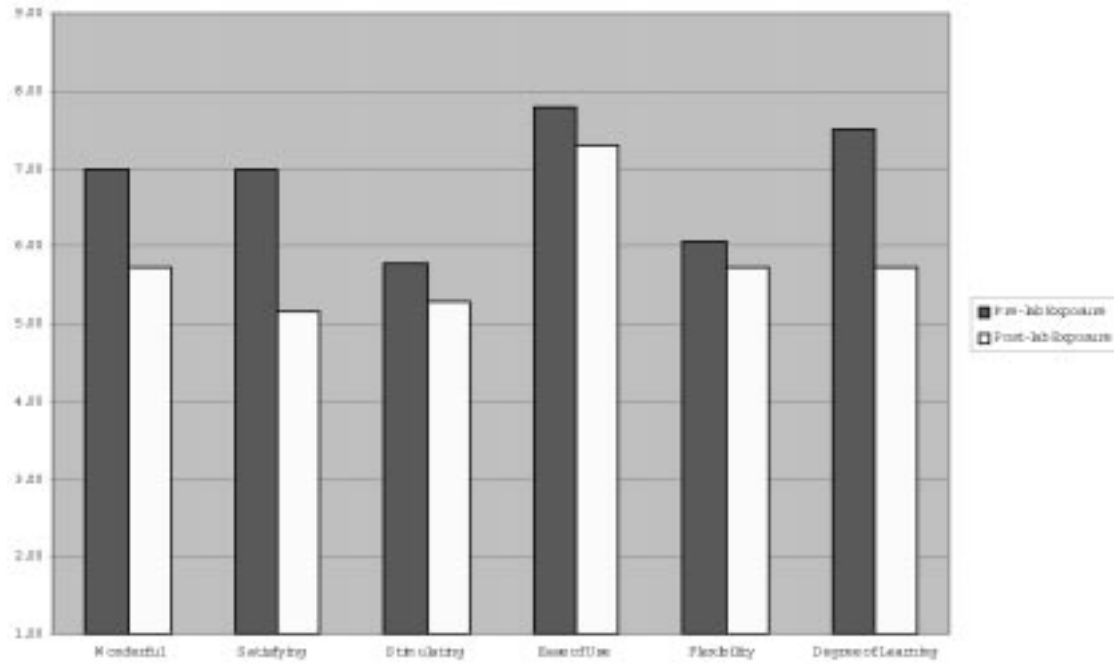


Fig. 8. Overall impressions pre- and post-lab exposure.

features (3 questions); and learning experience (4 questions). Each question contained a Likert scale ranging from 1 (negative evaluation) to 9 (positive evaluation). In terms of the overall impression, students were asked to evaluate the electronic lab using the following attributes: terrible-wonderful; frustrating-satisfying; dull-stimulating; difficult-easy; rigid-flexible; and learning nothing-learned new things. Figure 8 depicts the favorable means in each attribute category for the pre-exposure and post-exposure groups.

The second evaluation area measured student satisfaction with the various screen elements. Sanders and McCormick highlight the necessity of careful display design to include careful attention to icons and images, characters, screen organization, and adequate space [26]. Figure 9 depicts the favorable mean evaluation of screen elements for the pre-lab exposed and post-lab exposed groups.

A third evaluation area examines the organization and navigation of the electronic learning

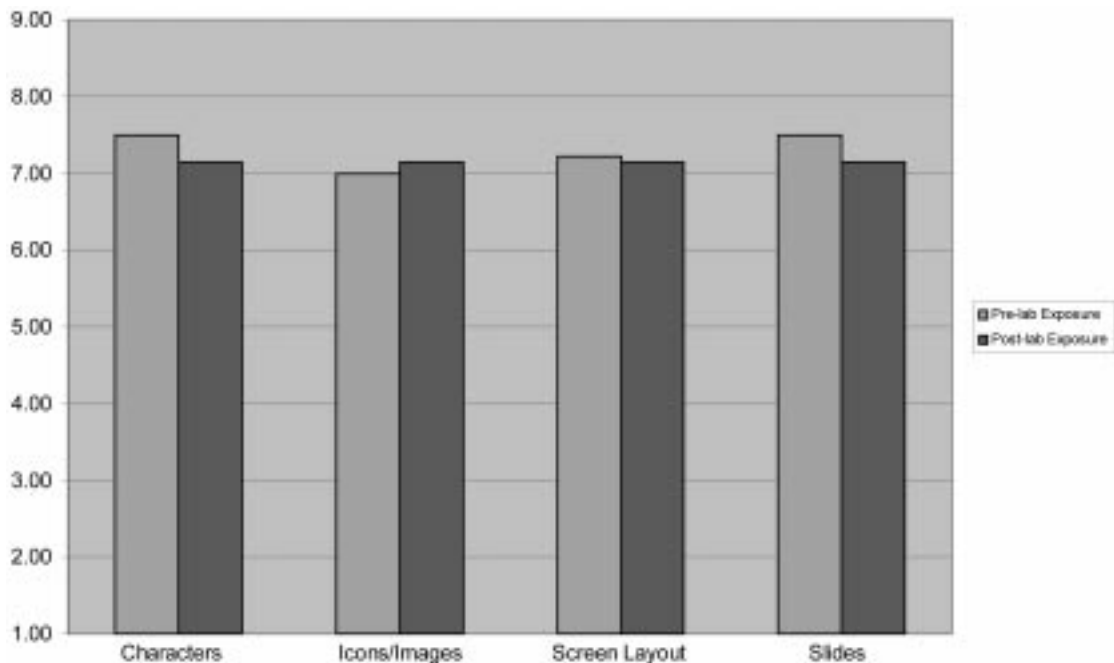


Fig. 9. Screen element evaluation.



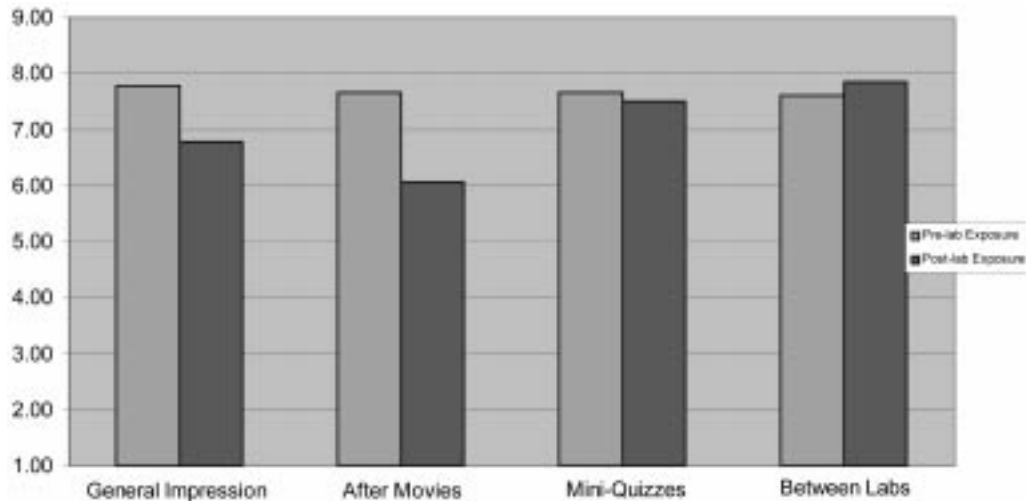


Fig. 10. Organization and navigation structure.

materials. Materials that are poorly organized and not strategically ordered can increase the amount of cognitive load for the student [27]. Figure 10 illustrates the favorable mean ratings for the navigation structure in terms of the general interface, after the movie clips, mini-quizzes, and between labs.

A fourth evaluation area involves the elemental course module features. Consistency among and within these features is critical to the success of any learning interface [28]. The survey instrument focused on three module elements that the author deemed most illustrative of the learning goals embedded in the software design. Feedback from the mini-quizzes provided students with immediate and evaluative information concerning their performance in the module. Secondly, movie clips helped to visually demonstrate the lab

processes as illustrated above. These visual descriptions are typically rated highly by students using electronic course materials [29]. A third course feature included the textual materials. Unlike a traditional classroom lecture or lab demonstration, students can explore through the information at their own pace and at their own speed. The authors wanted to evaluate the usefulness of the text material. Figure 11 suggests that students in both the pre and post exposure groups rated each element as valuable and positive.

In terms of the overall software experience, students in both groups indicated that the electronic labs enhanced/would have enhanced the learning process. Figure 12 illustrates this student feedback.

The usability study yielded two primary discussion points and paved the way for the next step in

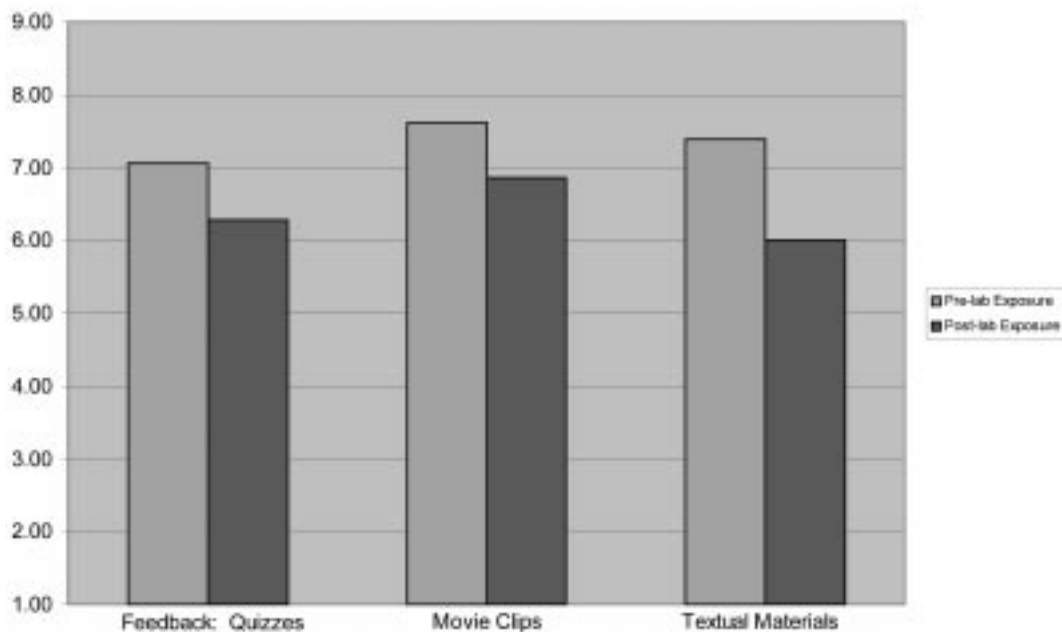


Fig. 11. Course module features.

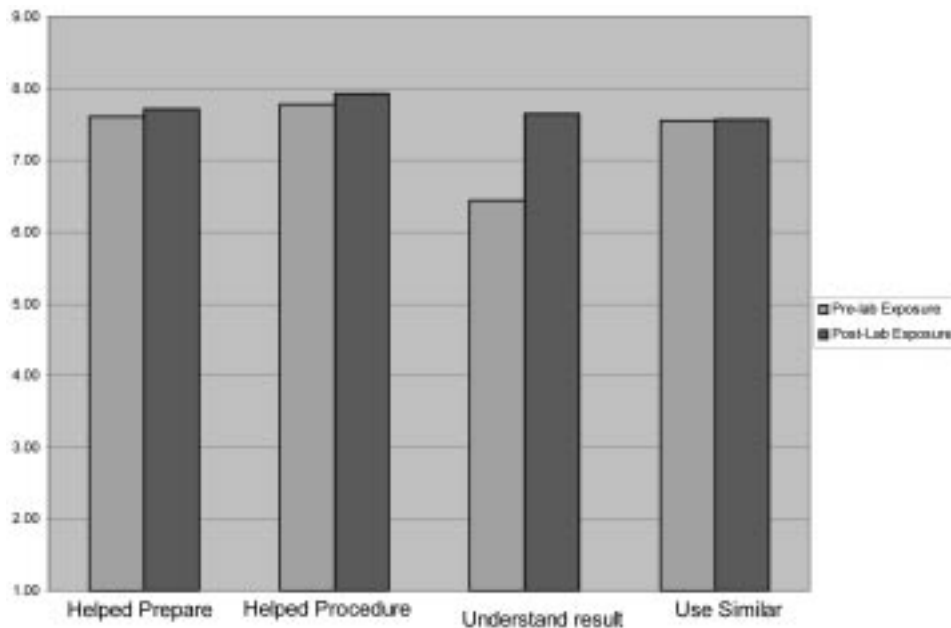


Fig. 12. Overall experience.

examining the efficacy of virtual lab instruction. Pre-exposure and post-exposure student responses yielded highly favorable impressions of the module organization, design, and effectiveness. As such, the authors found no major flaws in the design or presentation of lab materials and can conclude that the module design did not increase cognitive load and prohibit learning [30]. As the authors analyzed the quantitative and qualitative responses, we noted that students in the post-exposure lab reported a better understanding of the material. Hence, students that completed both the traditional lab and then the virtual lab reported a better understanding than those students that had just been exposed to the virtual lab when they responded. One simple explanation is that simple repeated exposure improves retention and recall, but another possibility is that the virtual laboratory supports declarative learning and the classroom exposure may support and encourage more procedural learning [31].

## CONCLUSIONS

The developed software has shown the potential to help the student in learning materials science concepts and procedures for laboratory experiments. The concept of a decision tree can enhance the student's experience with the software and bring it a step closer to the actual laboratory experience. More significant decision tree experiences can be designed for other experiments such as tensile testing of materials, heat treating of metals, hardness testing, and other similar experiments. The student quiz results taken immediately after they viewed the virtual experiment showed that the learning objectives were met and that the

software can be effective as a learning enhancement and textbook supplement tool. The general evaluation of the software, performed some time after the date of the quiz, showed that the students, in general, believe that the software was helpful and met the stated objectives. The evaluation results and the overall process also showed that the non-laboratory students are not very enthusiastic about working with a software and they resist such tools. However, if the software is required to be used as part of a course such as a laboratory course, this problem may be solved.

Additionally, the fully developed software can be used as a preparation tool for those engineering programs that offer a materials laboratory. The students can use the software to become familiar with the procedure, with the use of equipment, and with the pitfalls that they may encounter during the course of an actual experience. In those situations where a laboratory experience may not be available, such as at small universities and colleges in developing countries, the software can serve as a replacement experience. Advanced high school and junior college students can use this software to educate themselves about the activities that engineers undertake. Finally, the software can be used to train new teachers on this topic and help them devise similar structures in their laboratory practices.

As we progress through the digital age, educators must take care to ensure that pedagogy drives the development of technology tools and not visa versa. As universities experience declining budgets and increased demand for all resources, technology may provide some efficiencies and economies. However, these technology tools should be student-centered and pedagogically based. In the present development project and usability study,

the authors found that a virtual lab environment warrants full development and merits further empirical investigation. Our initial findings support the completion of software development and the implementation of a formal learning assessment.

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