Laboratory-Based STEM Education: Micro-computer Based Laboratories and Virtual Laboratories

S. Margoum[1(✉)], L. Daadaoui[2,3], and K. Berrada[3]

[1] Trans ERIE – Faculty of Sciences Semlalia, Cadi Ayyad University, Marrakech, Morocco
margoumsofia@gmail.com
[2] National Erasmus Office, Rabat, Morocco
[3] Mohammed V University, Rabat, Morocco

Abstract. Science, technology, engineering, and mathematics (STEM) education is critical to student's future success. It relies heavily on laboratory experiments, which are effective teaching tools to promote greater understanding among students. Many researchers have long urged educators to re-examine technology applications in the laboratory classroom so that students can gradually integrate a problem-solving approach that requires them to mobilize knowledge and skills in experimental science, mathematics, and technology. They will thus develop interdisciplinary processing expertise that will enable them to solve complex problems and promote the transfer of learning. Several tools can be used by modern education to achieve this goal. In this work, we are interested in the contribution of computer technology to educational practice through microcomputer-based laboratories MBL, and virtual laboratories in STEM. We evaluate the usefulness, effectiveness, and adaptability of these technologies in Moroccan universities; after an overview of the present state of the art regarding these technologies and laboratory styles in general. One of the most valuable contributions of computers to education comes in MBL form. By connecting probes to a computer with appropriate software, students can observe real-time data in various formats (formats (tables, graphs), giving them hands-on experience in real-time experiments. On the other hand, virtual labs can be an excellent way to perform activities that would otherwise be too time-consuming, dangerous, expensive, or impractical.

Research Contribution: The pervasiveness of technology in our lives has revolutionized the way young people learn and understand and has had a significant impact on education. This research argues that teaching and learning processes can be significantly improved by the incorporation of technology.

Keywords: STEM Education · Laboratories base teaching · MBL · virtual laboratories

1 Introduction

The training of future scientists, technicians and engineers requires serious reflection on the pedagogical model to be implemented to promote the learning of science and mathematics. This learning is most effective when it is built using an inquiry-based pedagogy

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articulated around technology and shaped by the systems engineering approach. Interest in science, technology, engineering, and mathematics (STEM) education models are exploding in the educational landscape. STEM education is an area that has received increased attention in recent decades, not only in education but also in business and entertainment. Universities are exploring STEM models as a way to restructure science and engineering education; the educational literature is replete with references to STEM initiatives, and experts and entrepreneurs are rushing into the education market with assurances that they, too, can help implement effective STEM programs [1, 2].

Each year, millions of students around the world participate in science experiments in in various disciplines to help them learn new skills and validate equations already covered in textbooks and lectures. Curriculum developers and teachers recognize the importance of these activities, which are fundamental to science education. [3].

STEM education encompasses the subjects' instructors are expected to teach, and the methods instructors use to teach STEM programs. STEM education also involves replacing traditional lecture-based teaching strategies with more inquiry-based and project-based approaches. The development of hands-on activities has been gradual over time and continues today. This development is related to changes in the goals of science education and improvements in instructional technology. Apprehension of scientific concepts, curiosity, motivation, hands-on science skills, problem solving, and understanding the nature of science are all educational goals that are fostered by laboratory activities. In recent years, emphasis has been placed on improving science education to develop the knowledge and skills needed in modern society concerning STEM education. In addition, the rapid growth of technology and globalization have significantly impacted scientific research, scientific training, and educational systems. [4].

2 Laboratory in Science

Laboratories are great places to teach and learn science. Especially since they offer students the opportunity to think, discuss, and solve real-world problems. It is hard to imagine learning to do science or learning about science without doing laboratory or fieldwork [5].

Over 160 years ago, the first laboratory course was formally introduced by Liebig in Giessen, Germany. Hands-on work was conducted as part of the lectures, which allowed for large numbers of students with minimal equipment and materials. The first institution to require practical work in physics was the Massachusetts Institution of Technology in 1869.

Laboratory courses then gradually expanded over the next fifty years until, in 1899, it was deemed necessary to allow students to perform experiments on their own. In the late twentieth century, more sophisticated solutions have been introduced to facilitate effective laboratory-based learning, including computer-assisted experimentation, simulations, virtual reality…

In 1982, Hofstein and Lunetta published a review of the role of the laboratory in science education, indicating that for more than a century, the laboratory has played a central and distinctive role in science education; and that science educators have suggested that the use of laboratory activities has many benefits for learning. On the other hand, they pointed out several methodological gaps in science education research that prevent a clear picture of the usefulness of the science laboratory in promoting student understanding [6–8]. Also, the level teachers prefer a safer "cookbook" approach where the student follows exact instructions without any comparison between their predictions and observations from actual experiments [9].

These shortcomings include.

- Insufficient control of the procedures and expectations set forth by the laboratory guide, teacher, and assessment system.
- Assessment measures of student learning outcomes that are inconsistent with stated objectives.
- Several deficiencies have been detected in the design, execution of processes, and procedures in the laboratory.

Ten years later, Tobin (1990) suggested that meaningful learning is possible in the laboratory if students have the opportunity to manipulate equipment and materials in an environment that allows them to construct their knowledge of related scientific phenomena and concepts [10]. Four years later, Roth (1994) suggested that although laboratories have long been recognized for their potential to facilitate the learning of science concepts and skills, this potential has not yet been fully achieved [11].

For 20 years, Hofstein and Lunetta (2004) have studied the circumstances that inhibit conceptual learning in science classrooms and laboratories [6]. In summary, the factors that continue to inhibit learning in science labs are:

- Assessment of knowledge, practical skills, and research objectives in the laboratory tends to be seriously neglected, even by high-stakes tests that claim to assess science standards. Thus, many students do not perceive lab work as particularly important to their learning.
- Many activities described in lab guides continue to offer lists of tasks to be followed in a ritualistic manner. They do not encourage students to think about the larger goals of their research and the sequence of tasks they need to complete to achieve those goals.
- Teachers and school administrators are often not well informed about the best professional practice, and they do not understand the reasoning behind these suggestions. Thus, there is a strong potential for disconnect between teacher theory and practice, which may influence learners' perceptions and behaviors during laboratory activities.
- The integration of science inquiry activities is hindered by limited resources, including access to appropriate technology tools and a lack of time for teachers to learn about, develop, and implement appropriate science programs. Other inhibiting factors include large numbers of students, lack of flexibility in organizing laboratory materials, and an emphasis on testing.

The advent of the computer has had an impact on laboratory training. It has opened up new possibilities, including simulation, automated data acquisition, remote control of instruments, and rapid data analysis and presentation.

Berger et al. (1994) separate the uses of computers for teaching or learning science into four categories: courseware, performance assessments, computer-assisted simulations, and computer-assisted experiments [12]. Courseware is generally exercises, multimedia documents that may contain hyperlinks, and computer-based presentations intended to be viewed by the student. Performance assessments are student assessments that are administered and compiled locally by a computer or remotely via the Internet, and that may highlight certain student needs to direct the student to resources that meet those needs. Computer-assisted simulations (Virtual labs), on the other hand, use the computer's calculation and display possibilities to simulate a phenomenon and represent it on the screen with different levels of complexity, interactivity, and realism. Finally, computer-assisted experiments (microcomputer-based laboratories) interact with a real experiment through an interface equipped with sensors and connected to a computer to collect, represent and analyze the data at different levels.

Several factors might be considered in trying to understand how lab sessions might be more formative. Lazarowitz and Tamir group these factors into five categories [13], which we summarize as follows:

- The program, includes all factors related to the curriculum, the choice of experiments conducted in the laboratory, and the links between these experiments and other learning activities;
- The resources include all factors related to the equipment available, the personnel who maintain the equipment, and the instructional materials that the teacher may use
- The learning context, which includes all factors associated with classroom climate, freedom of action, teamwork, student attitudes, and knowledge;
- Teaching effectiveness, includes all factors associated with the teacher's knowledge, skills, behaviors, and attitudes toward the subject matter and students
- Assessment strategies include all factors associated with different assessment methods and their influence on student attitudes and learning.

In STEM education, there are two different pedagogical approaches to be used in the labs depending on the goals to be achieved, the initial learning, and the learners' progression:

2.1 Inquiry-Based laboratory

A strong pedagogical approach is essential to laboratory instruction and science education in general. In the specialized sciences, where scientists conduct their research endeavors, experiments are deployed in support of theory development. In contrast, in the educational sciences, experiments serve a variety of pedagogical functions. Course designers must have adequate knowledge and expertise in educational theory and program development. Beyond the design and development of tools and methods, several pedagogical approaches have also been proposed in the literature on laboratory instruction [14–18].

Nowadays, practical work occupies an important place in science teaching. It has certain well-identified objectives such as: arousing students' interest in the subject and helping them to better understand science lessons, using a measuring device, evaluating the uncertainty of experimental measurement, and drawing a graph…..

In thinking about the role of practical work, it is important to keep in mind that the fundamental purpose of practical work is to help students make connections between the real world of objects, materials, and events, and the abstract world of thought and ideas [19–21]. These investigations often ask students to make connections between two domains of knowledge: the domain of objects and observables and the domain of ideas in which principles, theories, parameters, and quantities are found [22]. Ideally, an inquiry-based approach is implemented, in which students have the opportunity to plan an experiment, ask questions, hypothesize, and re-plan an experiment to test or reject their hypothesis. At the same time, teachers must explicitly link the activities, materials, and teaching strategies of the lab to desired student learning outcomes to ensure that the experiences in the lab are aligned with stated learning goals [8]. However, attempts to include the investigative approach in the general lab curriculum often result in disappointing practice that is different from what was intended, especially when student completion of investigative tasks is part of the course assessment.

This type of practice is likely to be most effective when:

- The learning objectives are clear and relatively few for a given task;
- An explicit strategy is used to stimulate student thinking beforehand so that the practical task answers a question the student is already thinking about;
- The task design supports students' efforts to make connections between the two knowledge domains.

2.2 Problem-Based Laboratory

In problem-based learning, learners are encouraged to solve the problems posed in a real-world setting instead of sitting in the lab and following the lab manual. It can be applied whenever possible to educational activities in which learners are confronted with a problem without a simple solution and seek adequate answers to the technological problems posed by adopting reasoning. Students were required to create their procedures for solving a problem and submit a written report describing the process, results obtained, and conclusions drawn. The emphasis was on developing testable hypotheses rather than finding the correct results.

Problem-based learning takes time and requires much more of the instructor and students than traditional instruction. Therefore, it cannot be the only method for all laboratory learning. However, many laboratory works seem to follow the set of procedures for this learning, such as those [23]:

- Identify a problem to be investigated and formulate a tentative hypothesis.
- Design an experiment to test the hypothesis.
- Experiment and record the results in appropriate forms.
- Interpret the results and evaluate the conclusions regarding the tested hypothesis.

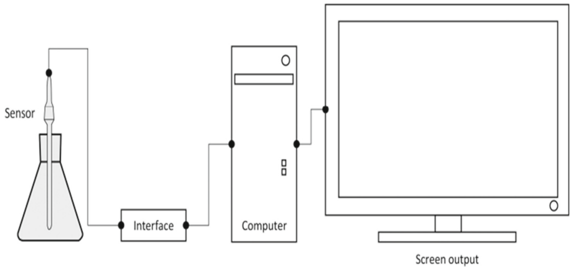

Fig. 1. MBL Setup

3 Micro-Computer Based Laboratories

Micro-computer Based Laboratories (MBL) is a term invented by Tinker and colleagues in 1983, and it has been used for nearly 40 years in science education. MBL represents one of the most valuable contributions of computers to education.

MBL labs typically involve using sensors or probes to directly collect data in electrical form and display it in digital and graphical form as it is collected. This real-time display significantly shortens the analysis and allows for immediate observation and control of experimental variables. The computer can then help students record and graph quantities such as force, light, position, pressure, temperature, heart rate, velocity, acceleration, brain waves, muscle signals, response time, and many other phenomena, see Fig. 1 [24]. It also allows these data to be presented as bar graphs, line graphs, or histograms, individually or together. These measurements can be recorded, analyzed in various ways, or printed. Students can change the scales of the graph before collecting the data and enter text describing the experiment performed; they can choose different time scales ranging from seconds to hours [25–28].

The development of MBL is one of the most promising additions to using computers in the science classroom. The enhancement of laboratory work through the use of MBL technology has received strong recommendations from many science teachers who take a constructivist approach to education. In addition, many researchers in the science field of education claim that employing this technology has clear advantages over a traditional laboratory for data collection and visualization.

MBL offers many advantages over traditional approaches. Among these, the following:

- Some variables are difficult to measure with traditional school equipment but easy to measure with a sensor, such as the pressure change of gases produced or consumed in a process; or the vapor pressure of a liquid.
- Students work with real-time graphs obtained instantly, not with pre-determined animations or interactive simulations previously prepared by the programmer.
- Presenting the graph on the screen in real-time saves students' time in class.
- The possible advantage is that the data acquisition time can be short so that students can have time to practice other skills.

- Newer generations of MBL systems allow users to perform time- or event-triggered data collection, observe events (via video capture) and collect data simultaneously, and present and analyze live data via remote sensors and wireless data interfaces.

Student's difficulties in solving qualitative problems are well known because they aren't asked enough to use qualitative argumentation in problem-solving. Indeed, we need to radically change the goals of laboratory experiments to improve the understanding of science. Instead of experiments emphasizing measurements, we need experiments emphasizing conceptual understanding. Experimentation, in particular, does not mean blindly trying things; but disciplined adherence to a fixed methodology [29].

4 Virtual Laboratories

Virtual laboratories allow interaction with a model that represents a real-time phenomenon. In the laboratory, simulation can, in some cases, replace reality. Some authors consider that simulation is probably one of the most promising and potent ways of using computers in teaching [30].

Several advantages of virtual labs over traditional labs are grouped here into four categories:

- In terms of diversity, simulations allow us to consider a larger range of values for the parameters of a studied phenomenon or allow us to interact with phenomena usually inaccessible.
- In terms of efficiency, simulations allow to simplify the experimental approach and limit the number of variables that can influence the progress of the experiment, thus reducing the time required for a given experiment.
- Attitudinally, simulations increase student motivation by allowing them to behave like real scientists and choose the experimental approach themselves.
- On the management side, simulations reduce the costs associated with the purchase and maintenance of equipment and require less handling before each experiment.

Virtual labs have several drawbacks that can be classified into two categories:

- Perceptually, simulations may present a simplistic view of reality; or introduce erroneous behaviors associated with the physical model used or the computer model of the physical model.
- From an attitudinal point of view, the frequent use of simulations can lead to computer dependency caused by an overemphasis on computer environments that appear simple and manageable as opposed to the complex and rebellious reality.

In addition to comparing virtual labs to traditional labs, we can ask whether the learning in virtual labs can replace the learning that occurs in traditional labs. Some authors propose that the role of simulations is not to replace traditional laboratories; but rather to allow students to become familiar with manipulations of variables that are not available in a real-time experiment. Others suggest that virtual labs are only truly beneficial to students when they have had the opportunity to perform real-time experiments on the same phenomenon [31, 32].

5 Context of Morocco

The difficulties encountered in our educational system are not only related to financial problems. The updating of information and pedagogical innovation also requires a commitment on the part of the teacher to update knowledge and propose practical solutions necessary for the proper understanding of scientific concepts.

In STEM, it will not be enough to provide students with textbooks or access to the Internet to develop a genuine scientific mindset; it will take an environment that allows students to produce knowledge from their experimental activity to make this reform a reality. The role of the teacher is essential; despite the contribution of new technologies, an excellent teacher with traditional methods will obtain better results than a mediocre teacher with even significant technological support.

The massification of the Moroccan higher education system in recent years, coupled with the reduction in the number of teachers, represents an enormous challenge in terms of pedagogical supervision, particularly in open-access institutions (vs institutions with competitive entrance examination). Until now, scientific training in our institutions has required much work and human involvement but little capital. The existing means of practical work material available to teachers in Moroccan public institutions are constantly deteriorating and need a lot of effort to be updated. Since 2003, when the new national education reform took place in Morocco, there has been a slight improvement in the need for teaching and research laboratory equipment. This evolution remains insufficient compared to the progress and expectations. More worryingly, due to a lack of equipment and human resources, several practical works have been removed from some of the first years' curricula.

To overcome the problem of practical work at Moroccan universities, a major initiative to introduce online simulation-based virtual laboratories in scientific teaching was conducted by the EXPERES project from 2016 to 2018. EXPERES (Information and Communication Technologies for Education applied to scientific experiments) is an Erasmus + Capacity building project with 12 Moroccan public universities and European partners from Spain and Finland. This project aims at exploiting the immense possibilities of the numerical tools of simulation widely available currently to set up a platform of virtual practical work (e-TP), making it possible for the students to carry out simulation manipulations of physics. It was decided to reproduce the modules of the physics program as virtual activities as presented in Fig. 2 [30].

All the institutions that teach science and technology have such a high number of students that they sometimes cut the most important part of the curriculum, namely the practical work.

Another project was a partnership between three universities, the University of Montreal, Cadi Ayyad University in Marrakech, and Mohammed V University in Rabat, called Microlab-ExAO: developing acquisition interfaces and sensors for a large-scale deployment of computer-assisted practical work.

The project aims to promote educational robotics in Morocco and transfer technological expertise from Montreal. This technology was developed in the robotics laboratory

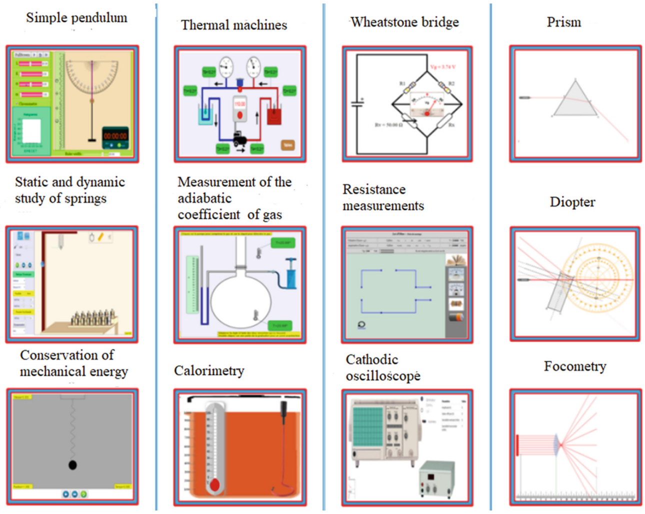

Fig. 2. The 12 practical activities scheduled for the physics modules in the first year.

of the Faculty of Education of the University of Montreal. The project was initiated almost eight years ago in Morocco; it consists of a transfer of expertise. The software sources of the technology along the way of development are given with nominal license; this contribution allows the Moroccans to manufacture this technology themselves. The MBL is already on the market, but its price is ten times higher than if it were produced in Morocco. It is a technology that should be included in the training or development of many science and technology-related skills.

The Microlab-ExAO project presents a solution; this unique, powerful, and versatile technology is composed of a microcontroller connected to several interchangeable sensors, software that can be used under Windows, and a didactic part intended to guide the student's reasoning. The home page is the first window that the student accesses when launching the software. It is shown in Fig. 3. It provides access to the main functions of the software and shows the various sensors connected to the interface.

This unique system allows the student to familiarize himself with physical and chemical phenomena by building his assembly. In addition to its ease of use and low cost, the added value of this technology lies mainly in the significant autonomy left to the student: the teacher plays only a secondary role because the learning process does not require supervision. This robust system has proven itself for over 30 years and is currently used in several countries [29, 34].

Following the implementation of the virtual laboratory of physics at Cadi Ayyad University of Marrakech, a survey was conducted to assess the satisfaction of learners. The survey questions were designed to assess learner experience with the platform and the virtual lab activities. 120 students took part in this survey, 53.33% stated that the implementation of the platform was very satisfactory, and 35.83% stated that it was satisfactory. Based on their responses, students appreciated the new hands-on environment and were encouraged to study more successfully. They also urged that more virtual

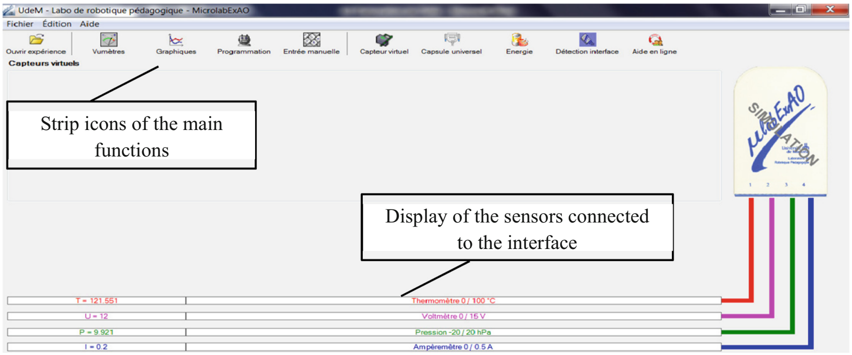

Fig. 3. The homepage window

activities should be added to the platform to cover all chapters of the physics course. It has been shown that the use of virtual labs can have a favorable influence on students' attitudes, knowledge, and skills [30]. For instructors, over 80% of them support the development of a virtual environment as a means of preserving laboratory activities and their benefits for enhancing learning [30]. However, resistance to virtual labs persists [33], due to some science teachers' reservations about replacing traditional, hands-on, face-to-face labs with virtual ones. The reluctance also comes from a lack of awareness of the potential of these technologies, the absence of technical and pedagogical support and a negative perception as an extra activity.

These experiences remain very limited and deserve to be generalized as part of a national strategy for the use of digitalization in practical activities. This strategy should include training and support for teachers (technical and pedagogical) and an improvement of infrastructure and equipment but also a recognition for the effort put into these activities and their development for the professor's career.

6 Conclusion

In this paper, we present a summary of the state-of-the-art in MBL and Virtual Laboratories and their role in the Education of STEM in laboratories.

The problem, in Morocco and elsewhere, is that there is no environment more resistant to change than the academic environment. We need to open up, communicate, get involved, and look for licenses, property rights, and patents. Because as far as this generation is concerned, we have missed the succession. Faced with the problem of massification, which is pejorative, we should democratize higher education. It is crucial to emphasize the urgency of an ambitious reform of STEM education in Morocco, as the use of STEM has become a matter of course in our socio-professional practices and the creation of new job opportunities.

Recently, many projects and cooperation programs have aimed at integrating new emerging technologies in education to develop innovative learning solutions for the educational system in Morocco. A solution can be provided by integrating MBL and simulation in the framework of new educational technologies, or even by combining them.

In this article, we share the experience of two major Moroccan experiences through the integration of virtual laboratories and the MBL; we can say that the feedback has been positive by learners and educators. This integration aims not only to make the practical work more effective but also to improve their content and quality, to reduce the cost and time frame for their execution.

We know from experience that scientific reasoning cannot be acquired after a single experiment. It is indeed necessary to carry out many experiments in the laboratory so that learners acquire, through practice, the experimental approach. The main idea of this research is to multiply the opportunities for this practice by taking advantage of the efficiency and usefulness of MBLs and virtual laboratories.

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