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# Board 86: Utilization of Inexpensive, Safe, and Portable Electronic Instrumentation System to Increase Students' Performance in Multiple Stem Disciplines

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Pursuing continuous financial support is an integral part of Dr. Rahman's research agenda Over the years, Dr. Rahman ¬received (as both PI and Co-PI) several competitive grants for both Imaging Informatics and

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# Utilization of Inexpensive, Safe, and Portable Electronic Instrumentation Systems to Increase Students' Performance in Multiple Stem Disciplines


## Abstract

The experiment-centric pedagogy (ECP) teaching approach is a less cumbersome way of introducing core and fundamental topics in STEM through relevant practical and hands-on sessions that are carefully incorporated into lectures. The philosophy of ECP is that students learn better by doing. Hence, it promotes the practical implementation of fundamental theories in STEM fields by using inexpensive basic elements to develop portable but extremely effective units for use by these students. The portability of these units enables these students to conduct these experiments in the comfort of their homes, while their low cost makes it highly affordable. With carefully curated experiments across different departments such as Electrical, Civil, Physics, and Computer Science, ECP has been able to develop informative experiments to calculate impedance and transient current in RLC circuits buttressing the concept of ohm's law in electrical engineering and physics, combinational and sequential circuits such as adders, multiplexer, subtractors, decoders, counters, and shift-registers in computer Science. ECP also implemented data acquisition systems alongside experiments to demonstrate Hooke's law with respect to stress/strain on a flat metal bar and measurement of the pressure of a thin-walled cylindrical vessel in civil engineering. These experiments help students develop a good understanding of these concepts, which are the building blocks of their respective fields. Early results of ECP have shown that there has been a significant improvement in students' interest in these STEM courses.


## Introduction

The experiment-centric pedagogy (ECP) teaching approach is a system of teaching core and fundamental topics in STEM through relevant experimental sessions that are carefully incorporated into lectures using miniature devices. The philosophy of ECP is that students learn better by doing. Hence, it promotes the practical implementation of fundamental theories in STEM fields by using inexpensive and less cumbersome technological tools to communicate effectively core and basic concepts in different STEM fields. The portability of these units enables these students to conduct these experiments at the comfort of their homes, while their low cost makes it highly affordable. As opined by Connor et al [1], due to the portability of ECP systems, many instrumentation-based courses and lab-based learning experiences can now be held in normal classrooms, even at home, rather than in specially outfitted facilities. Consequently, since many concepts in the STEM field can be demonstrated through instrumentation, with carefully curated experiments across instrumentation-based courses in different disciplines such as electrical engineering, civil engineering, physics, and computer science, ECP has been able to develop informative experiments to demonstrate to calculate impedance and transient current in an RLC circuit in electrical engineering, combinational and sequential circuits such as adders, multiplexer, subtractors, decoders, counters, and shift registers in Computer Science. ECP also implemented data acquisition systems alongside experiments to demonstrate Hooke's law with respect to stress/strain on a flat metal bar and measurement of the pressure of a thin-walled cylindrical vessel in civil engineering. The inexpensive, safe, and portable electronic systems utilized are basic resistors, cables, integrated circuits, led displays Analog Devices Active Learning Module 1000 (ADALM 1000 aka M1K), Analog Devices Active Learning Module 2000 (ADALM 2000 aka M2K) and the Arduino microcontroller system [2]. When these systems are paired with appropriate software and sensors, they are used to measure a wide range of properties, from vibration to oxygen levels. In this paper, details of these experiments are highlighted as well as students' assessment of the benefits of ECP in their STEM learning.

**Theoretical Underpinning of ECP**

ECP is anchored in inquiry-based and constructivist learning theories. According to the National Research Council [3] and Savey [4], inquiry-based learning (IBL) is a pedagogical approach in which students begin with a question followed by investigating the solutions, reflecting, and communicating findings, and creating new knowledge based on the collected evidence. IBL has been widely adopted in science education because of its great potential to facilitate more positive student attitudes and a deeper understanding of scientific concepts [5], [6]. Additionally, according to Specht et al [7], inquiry-based learning has been increasingly suggested as an efficient approach for fostering students' curiosity and motivation by linking science teaching in schools with informal learning and phenomena in everyday life. To ensure the identification of the opportunities for exercising learning agency in inquiry-based learning supported with mobile technology, Suarez et al [6] proposed six dimensions of the analytic framework for inquiry-based learning theory (control over goals, control over content, control over actions, control over strategies, options for reflection, and options for monitoring) (Figure 1). Suarez et al [6] further used these analytical dimensions to evaluate 12 types of mobile activities derived from direct instruction (i. location guidance, ii. procedural guidance, iii. metacognitive guidance); access to content (iv. fixed content, v. dynamic content); data collection (vi. data collection, vii. collaborative data collection); peer-to peer interaction (viii. Social asynchronous, ix. Social synchronous); and contextual support (x. augmented experience, xi. Immersive experience, and xii. adaptive feedback) type of mobile activities. As shown by Suarez et al. [6], an indication of what aspects of the learner's agency can be exercised with the different types of mobile activities. The types of mobile activities that support more learners' agency are located on the positive side, while those that offer fewer opportunities for learners' agency are located on the negative axis.

Brush and Saye [8] argued that knowledge is constructed by individuals rather than taught by others which emphasizes the concept of student-centered learning. This concepted are supported by well-established theories like constructivist theory and related cognitive theory, humanism theory and social interaction theory. Yair [9] further opined that constructivism elucidates the cognitive law of human learning, demonstrating how learning occurs, how learning is constructed, and the role of the learning environment in knowledge construction. Based on their experiences or encounters, learners construct new information [10]-[12]. According to Clark [13], constructivism spurs discovery learning when instructors indirectly provide learners with the information and resources necessary for them to construct or discover the content individually or collaboratively.

Clark [14] observed that self-determination theory research has placed a large amount of attention on not only intrinsic motivation but also extrinsic motivation.

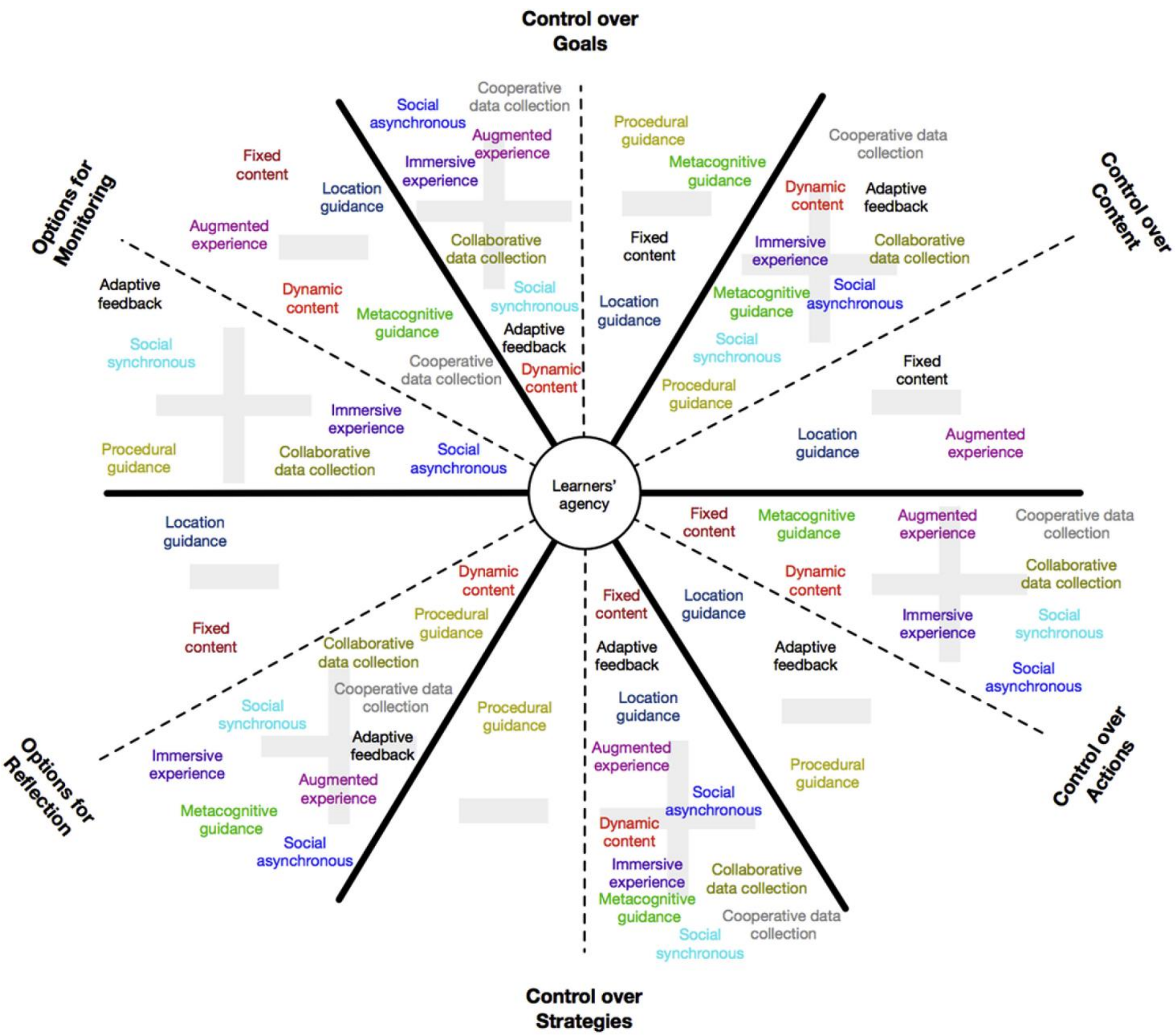


**Figure 1: Six-Dimension Framework of Active-Learning (Source: Suarez et al [6])**

ECP is anchored both in inquiry-based and constructivist learning, as learners are provoked and stimulated when the learning phase commences at the experimental phase rather than commencing at the traditional phase of science and information. Learners are highly curious and motivated as they start to discover the concepts/theory behind the phenomenon observed in the experimental phase. This ultimately encourages active engagement; promotes motivation, autonomy, and responsibility; develops creativity and problem-solving skills; and tailors learning experiences to each learner, which are the special attributes of discovery learning [15].

## Methodology

Experiments are carefully developed in the STEM field. The following are the criteria utilized in selecting courses where ECP will be implemented:

1. Courses where electronic instrumentation is used to acquire experimentation data.
2. Adequately developed course structure with modules where ECP can easily be implemented.
3. Adequate knowledge of the existing probes/sensors/interface that is currently utilized in experimental data acquisition.
4. Feasibility of conversion of the probes/sensors/interface to electrical signals that can be connected to an ECP device.
5. Ability to design a course module aligned with the ECP template.

Based on the above criteria, ECP experiments were developed to demonstrate the concepts of RLC circuits, ohm's law in electrical engineering/physics, combinational and sequential circuits such as adders, multiplexer, subtractors, decoders, counters, and shift registers in computer science. ECP also implemented data acquisition systems alongside experiments to demonstrate Hooke's law with respect to stress/strain on a flat metal bar. A circuit to measure the pressure of a thin-walled cylindrical vessel in civil engineering was also developed.

### Civil Engineering

In addition to conducting experiments to show the correlation between stress/strain on a flat metal bar and the application of Hooke's law, as well as measuring the pressure of a thin-walled cylindrical vessel in the field of civil engineering, ECP also set up data acquisition systems.

### Stress/strain on a Flat Metal Bar

To demonstrate Hook's law, the experiment estimates the stress induced on a cantilever steel beam through voltage readings from a strain gauge attached to the beam. The voltage difference resulting from the strain deformation is proportional to the strain and is of a relatively high magnitude. An ADALM1000 digital logging system is used to log the potential difference as a result of deforming the steel bar through as attached strain gauge sensor. The circuit board has an input voltage supply of 5 V which serves as a voltage source to the strain gauge. The components of the circuit include bread board, resistors, wires, and amplifier. To read the voltage generated from deflecting the beam, the circuit board is connected to the strain gage, and the +5 Volts is supplied via a connection between the ADLM 1000 and the circuit board. After the connection, the following are carried out: (i) The beam is clamped at 12.5 inches away from the end of the bench. Figure 2a shows the position where the beam should be clamped. (ii) The ADLM 1000 USB cord is connected to the computer. (iii) The Alice M1K voltmeter is launched on your desktop. Finally, (iv) the voltmeter reads the voltage upon displacement of the beam (Figure 2b Circuit Diagram).

**Figure 2a: The Position Where the Beam is Clamped**

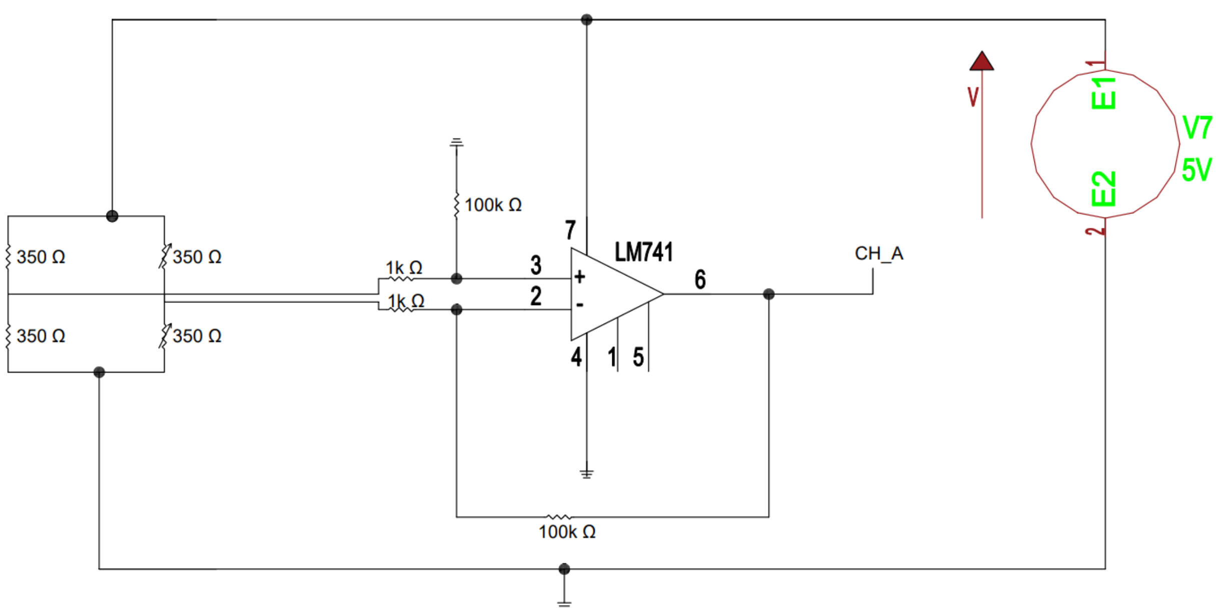


**Figure 2b: Circuit Diagram**

**Thin-walled cylindrical vessel**

The thin-walled cylindrical vessel is designed to teach the concept of circumferential and axial stress in thin-walled vessels in the mechanics of materials course. To demonstrate this concept, a strain gauge is connected to a soda can prior to it being popped open. The strain gauge is then connected to a data acquisition system developed using the Arduino microcontroller system [16].

For the data acquisition system, a Wheatstone bridge was developed to measure the real-time change in the internal pressure in the thin wall vessel once the soda was opened. For this, a strain gauge is attached to the external wall of a soda can and connected to an arm of a wheatstone bridge. Once the soda can be opened, the strain gauge records changes in pressure. Strain gauges have a resistance response to strain; hence, a potentiometer attached to the Wheatstone bridge enables the determination of the output of the strain gauges at different times while the pressure of the thin-walled vessel changes. The analog output from the Wheatstone bridge circuit is then fed into a 16-bit analog to digital converter (ADC).

The second unit of this design consists of the Arduino microcontroller. The Arduino system takes input from the ADC, processes the signal then displays the changing voltage on the associated LED output.

The last part is the LED output that displays a log of the 5 latest voltages. These voltages are logged by the Arduino system as the pressure of the soda can decreases. The displayed voltage on the LED circuit is real-time, and our design is implemented to account for the tiny change in thin-walled strain and displays such a value as a voltage change. Equation 1 shows the transfer function for converting the strain/strain to voltage. The measurement through a transform function is converted to the drop in pressure in the soda can.

$$\boldsymbol{\Delta P} = \frac{E\frac{4\frac{\delta E}{Ei}}{GF(1-2\frac{\delta Eo}{Ei})}t}{[r(1-\frac{\vartheta}{2})]} \qquad (1)$$

where $\Delta P$ is the ambient pressure from the Wheatstone bridge deflection voltage as the can's interior pressure is released down to atmospheric pressure, E is Young's modulus of the wall material, $\delta Eo$ is the bridge deflection voltage as one of the arm's resistances changes by $\delta R$ from the initial resistance $R$ in a bridge where other arms have equal resistances of $R$, and $Ei$ is the input voltage to the bridge. GF is the gauge factor that is specific for the strain gauge, while t is the wall thickness of the material, $r$ is the radius of the pressure vessel, and $\vartheta$ is the Poisson ratio of the material.

**Physics**

Knowledge acquisition has been aided by ECP through a hands-on device in the physics department. To improve students' knowledge on the subject, a physical representation of ohm's law was provided. Ohm's law, which states that the amount of steady current through a metallic conductor is directly proportional to the potential difference across the material's terminals, describes the relationship between current, voltage, and resistance. Equation 2 is used to represent this relationship.

$$V = IR \quad (2)$$

where V is the potential difference across the resistor, I represents the applied current through the resistor, and R is the resistance of the resistor. Students were provided with device that included the ADALM 1000, breadboard, Alice software, resistor ratings of 300, 470, 680, and 120 W, as well as connecting wires. The procedure was demonstrated by the instructor, and the students followed suit. Prior to the class, Alice software was installed on all of the computers. Different resistor ratings were placed on the breadboard, and the ADALM 1000's channel A (CHA) and ground (GND) were connected to both ends of the resistor using the breadboard and jumper wires provided. The ADALM 1000 device was connected to the computer via a USB cable. This device provides power to the breadboard as well as visuals of the quantities being measured. Figures 3a and 3b show how connections were made in both series and parallel respectively. The voltage graph was plotted against the applied currents. The overall resistance of each connection was measured. In the Ohm's law experiment, the value of the theoretical calculations was also used to observe the difference between the analytical method and the theoretical method of circuiting.

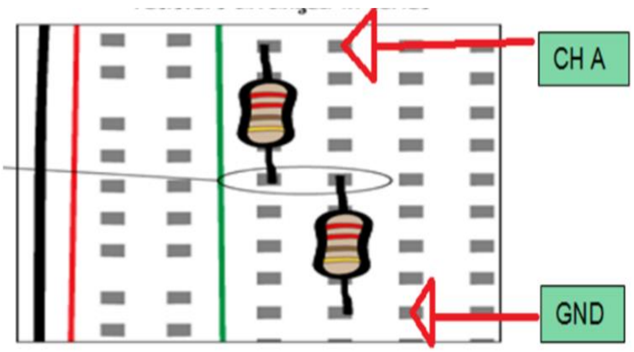


**Figure 3a: Series connection of the resistor**

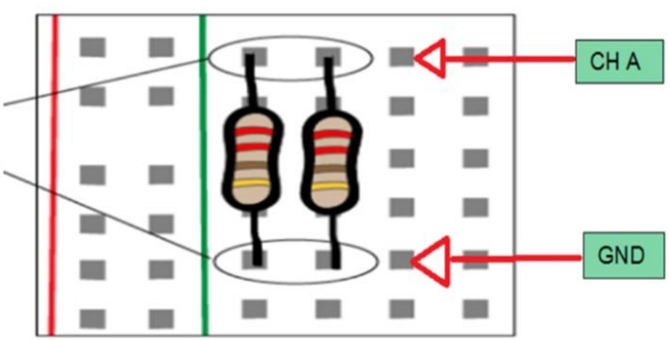


**Figure 3b: Parallel connection of the resistor**

The rate of charging and discharging a capacitor, known as the Resistor-Capacitor (RC) time constant, was implemented by the students in another set of experiments using an ECP hands-on device. The students were given kits containing 1 microfarad, a 2.2 kW resistor, and an ADALM 1000 device. The connection layout shown in Figures 4a and 4b was used as a setup guide with the software. The steps followed by the students to set up these circuits includes: Set the minimum and maximum values of channel A of the arbitrary waveform generator (AWG) to 0.5 V and 4.5 V, respectively, to apply a peak-peak square waveform centered on 2.5 V as the circuit's input voltage. The source voltage measure current (SVMI) mode was chosen from the AWG A drop-down menu as a square waveform menu. Channel A's frequency was set to 15 Hz, and Hi-Z mode was chosen from the AWG B mode drop-down menu. CA-V and CB-V were chosen for display from the ALICE curves drop-down menu. From the trigger drop-down menu, CA-V and auto Level were chosen. The time base was changed until two square wave cycles were visible on the grid. All of these settings were made on the software, as shown in Figure 4c. On the Alice software, the students were able to determine how long it takes for the capacitor to reach full charge from the time the voltage is turned on and how long it takes for it to decay to 0 V when turned off. For a known capacitor value, the slope of the graph against time (t) was used to calculate the unknown resistor's value. Students were allowed to go through this process to see how deep their critical thinking and problem-solving abilities were and how they could note and correct errors. However, the instructor and graduate students were available to answer the students' questions.

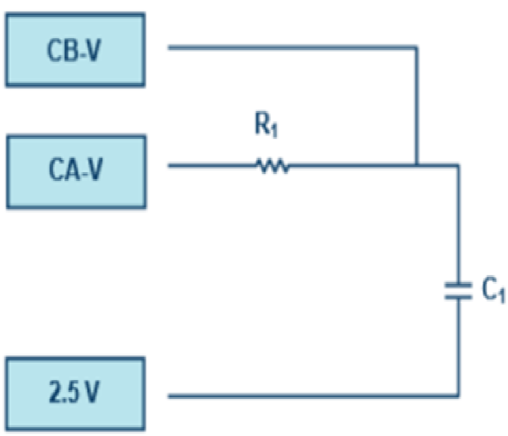


Figure 4a: Circuit diagram of the RC experiment

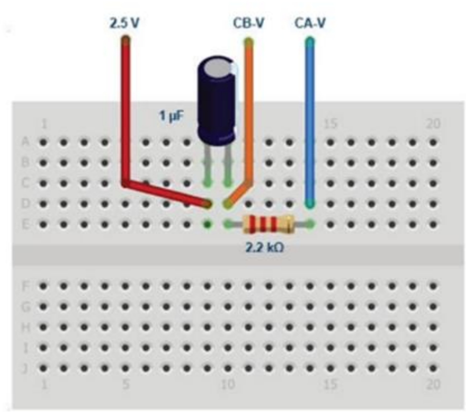


Figure 4b: Circuit connection on the breadboard of the RC experiment

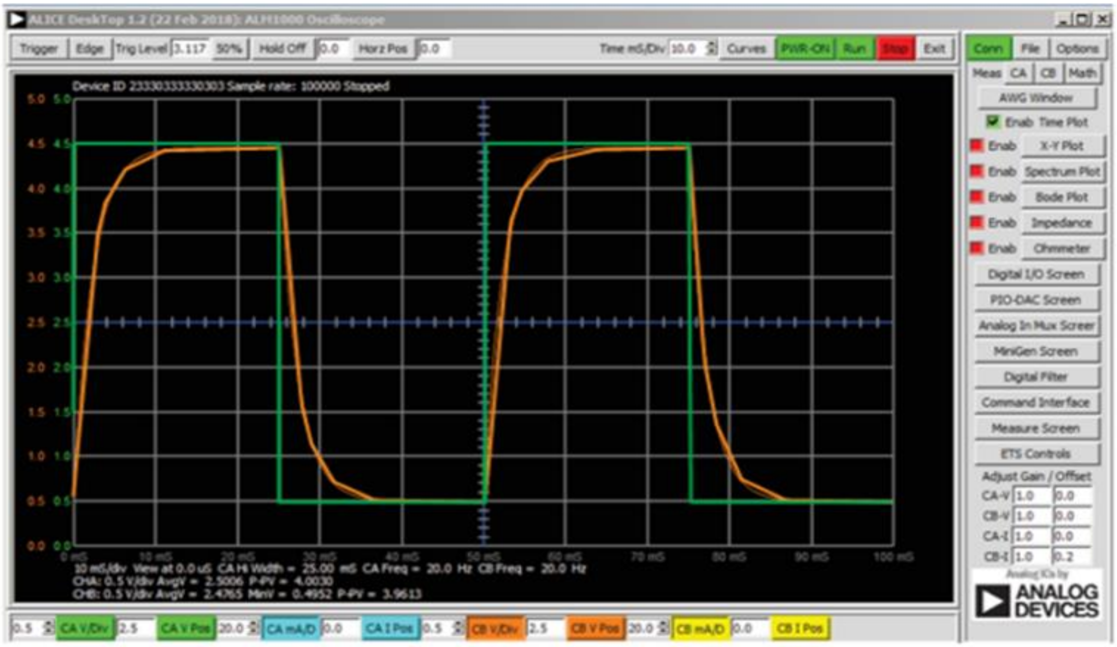

**Figure 4c: Pictorial representation of the ADALM 1000 output result for the RC experiment**

### Computer Science

Computer systems are at the foundation of major breakthroughs in information and communication technology (find any paper and cite here). At the heart of these systems lies digital circuits, which necessitated the expansion of the ECP project to the computer science department. The objective of the carefully curated experiments is to drive down the concept of digital circuits by giving the students practical and hands-on experience of the theoretical concepts. Experiments are developed to demonstrate the operations of digital circuits such as AND, OR, NOT, adders, decoders, counters, multiplexers, registers, and shift-registers. These circuits are at the core of all major digital circuits used in industries and ICT in general. These circuits are built using inexpensive electronic components and are designed to be portable, allowing the students to carry out these experiments at the comfort of their homes.

A logic gate is a component that serves as a foundation for digital circuitry. They carry out elementary logical operations that are crucial to digital circuitry. Logic gates in a circuit will decide what to do based on a combination of digital signals flowing into their inputs. Figures 5a and 5b show the connections of ICs to pin no. 14 to the ADALM1000 5 V output and pin no. 7 to the ground. For this experiment, the power supply was taken from the M1K system. The voltage output of the circuit is read and logged through the M1K system to enable us to establish the output voltage that corresponds to a logic of 1 or 0 signifying the On or OFF position for the gate. LED indicators are also connected at the gate output to show the state of the gate. Figure 6 shows the counter setup and the different LED that indicates the state of each gate. Through these LEDs, students can take note of the number being counted by the counter circuit.

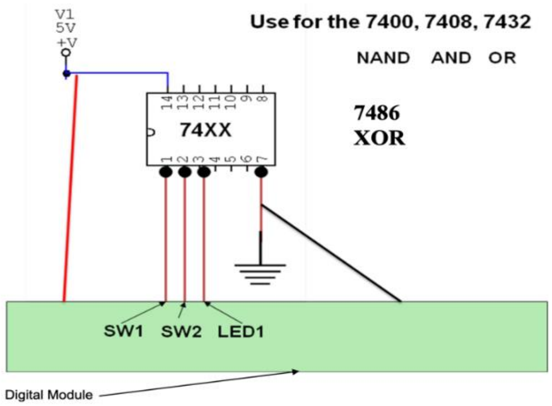


**Figure 5a: Connections**

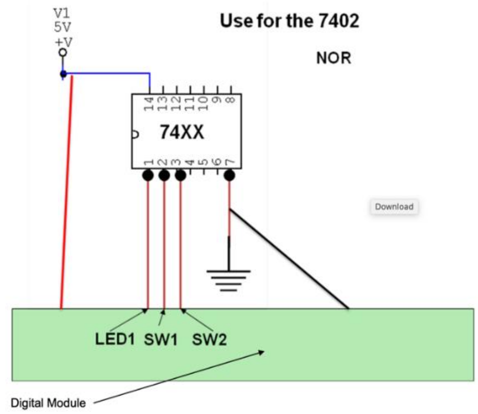


**Figure 5b: Connections**

Figure 6 shows a student performing an experiment using one of the devices developed in the ECP project. By adopting ECP, students were able to have a better understanding in the course (COSC 243 – Computer Architecture) and other STEM subjects that are part of the project.

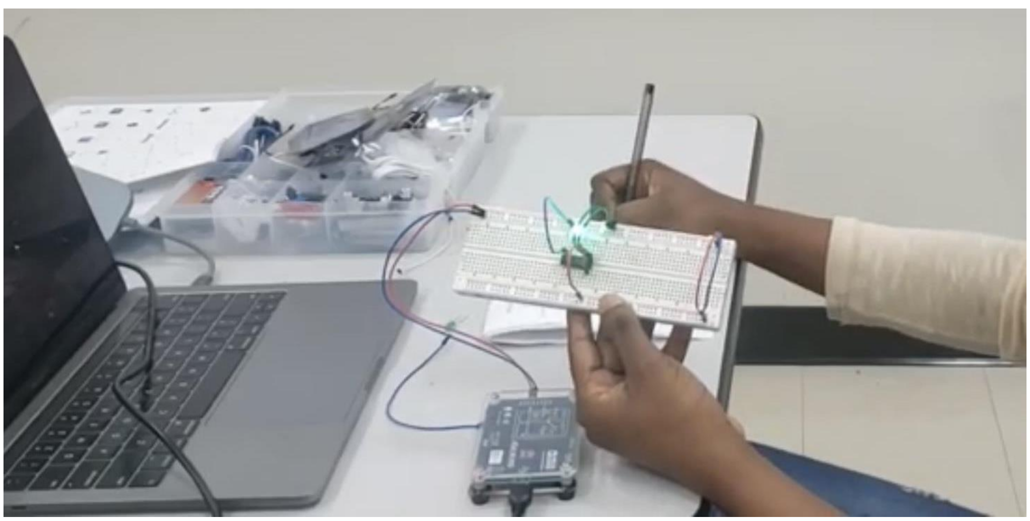

Figure 6: Students setting up the experiment.

The Motivated Strategies for Learning Questionnaire (MSLQ) developed by Pintrich, Smith, García, and McKeachie [15] was used to measure key constructs associated with students' success, such as motivation, epistemic and perceptual curiosity, and self-efficacy. The effectiveness of the implementation of ECP was evaluated using the MLSQ measure, which consists of a learning goals scale that is further divided into cognitive and resource management strategies components. The cognitive component measures rehearsal, elaboration, organization, critical thinking, and metacognitive self-regulation, while the resource management strategies component includes time and study environment, effort regulation, peer learning, and help-seeking items. Positive gains are expected when pre and post-data are collected, particularly in intrinsic goal orientation, task value, control beliefs, and self-efficacy, with reduced test anxiety from the motivational scale. In addition, improvements are anticipated in critical thinking, metacognitive self-regulation, peer learning goals scale, especially as a result of the active learning strategies and the implementation of ECP. The key constructs are measured using a 7-point Likert-type scale in the MSLQ. On the other hand, the Littman and Spielberger assessment tool evaluates the level of curiosity in students (11). This tool consists of two categories: Epistemic Curiosity and Perceptual Curiosity. Epistemic Curiosity (EC) is motivated by the desire to learn, gather knowledge, and fill gaps in one's understanding. In contrast, Perceptual Curiosity (PC) results in enhanced perceptual experiences for the individual. The assessment tool utilizes a 4-point Likert-type scale. A 6 items 5-scale Likert was used to collect responses on perceptions of the use of devices, a 4 items 5-scale Likert was also used to collect responses on perception of learners about the pedagogy. A descriptive analysis is performed to determine the significance of the pre- and post-test results for all key constructs using simple percentage, mean, standard deviation. More so, inferential statistics was carried out using a parametric approach (t-test) to compare the pre- and post-test responses of the students. All statistical analyses were caried out using IBM SPSS 25.0 at a confidence level of 95.0%.

## Results and Discussion

Table 1 presents the courses and the distribution of participants that were considered in this study. A total of 170 participants were recruited for the present study and the responses were analyzed and presented.

**Table 1: Distribution of Participants in Spring and Fall 2022**

| Term | Department | Course | Number of Learners |
|---|---|---|---|
| Spring 2022 | Civil Engineering | Environmental Engineering | 12 |
| | Civil Engineering | Statics | 7 |
| | Civil Engineering | Transportation Engineering | 16 |
| | Computer Science | Computer Architecture | 13 |
| | Physics | University Physics II | 9 |
| Fall 2022 | Physics | University Physics I | 23 |
| | Computer | Computer Architecture | 20 |
| | Civil Engineering | Environmental Engineering | 7 |
| | | Total | 107 |

The mean scores of the learners’ response to the MLSQ in the pre-and post-test are presented in Table 2. Overall, there was a significant improvement in the test anxiety scores of respondents, critical thinking, and peer learning and collaboration ($p<0.05$). However, a significant reduction in extrinsic goal orientation scores ($p>0.05$) was observed. Using experiment-centric pedagogy helps learners engage actively in the learning process, hence improving critical thinking. This has also been found true in the literature. Dole et al. [17] reported after an experimental design study that students' presentation after engaging with hands-on devices reflected improvement in critical thinking and peer learning competencies. This stressed the importance of student-centered learning, hence strengthening the result that hands-on learning with miniature devices can boost critical thinking skills among learners. Test anxiety can lead students to postpone fulfilling their obligations and perform their tasks with less proficiency [18]. Additionally, the literature has shown that test anxiety can determine the academic performance of learners [19]. An improvement in learners’ test anxiety simply means it is lowered, and hence, learners can focus on the task at hand and bring their best into their individual responsibilities in learning. Using a problem-based learning (PBL) approach, Erdem [18] reported that PBL had no significant influence on learners’ test anxiety. The present study findings and literature therefore revealed that experiment-centered learning can significantly lower the test anxiety of respondents. Peer-learning collaboration involves the active participation of two or more learners in understanding concepts in different STEM fields. Krajcik and Czerniak [20] mentioned that when students work together to solve the central problem, they gain comprehension of the linked ideas. According to the results of the present study, learners were found to have improved in peer learning, and the literature also posited that peer learning improves overall performance and learning outcomes [21], [22].

**Table 2: Mean Scores of Motivated Strategies learning Questionnaire Subscales (N=107)**

| Motivation Subscale[1] | Pretest | Post-Test | t test | *p value* |
|---|---|---|---|---|
| Intrinsic Goal Orientation[1] | 5.48±1.22 | 5.47±1.21 | 0.11 | 0.92 |
| Extrinsic Goal Orientation[1]* | 5.94±1.24 | 5.56±1.13 | 2.41 | 0.02 |
| Task Value[1] | 5.59±1.31 | 5.65±1.18 | 0.50 | 0.62 |
| Expectancy Component[1] | 5.66±1.29 | 5.68±1.19 | 0.17 | 0.86 |
| Test Anxiety[1]* | 4.56±1.87 | 4.87±1.86 | 2.31 | 0.02 |
| Critical Thinking[1]* | 4.9±1.47 | 5.26±1.24 | 2.67 | 0.01 |
| Metacognition[1] | 5.19±1.29 | 5.41±1.07 | 1.86 | 0.07 |
| Peer Learning and Collaboration[1]* | 4.17±1.72 | 4.73±1.49 | 3.51 | 0.01 |
| Interest-type Epistemic Curiosity[2] | 3.16±0.64 | 3.14±0.63 | 0.52 | 0.61 |
| Deprivation-type Epistemic Curiosity[2] | 2.65±0.65 | 2.68±0.65 | 0.45 | 0.65 |

*Significant differences exist between pre and post-test mean scores ($p<0.05$)
[1] 1-7 Likert Scale
[2] 1-4 Likert Scale

Figure 6 presents the perception of learners about the inexpensive, safe, and portable electronic instrumentation systems. The perception of learners on the use of hands-on tools revealed that a larger percentage accepted that the use of the devices suited their learning goals (54.39%), and it also reflected real practice (57.89%). From the results, it was observed that 66.67% mentioned that the devices provided the opportunity to practice course content. When learners are given the opportunity to interact with devices outside the traditional classroom, a report showed that they find it more engaging and real with regard to what they are learning [23]. Learners agree that hands-on devices are highly relevant to what they are learning, and such a response demonstrates that the learning process is no longer passive but rather active and engaging.

The feedback of the learners on the use of the devices revealed that a larger proportion (56.14%) agreed that the devices definitely improved their understanding of the course concepts (Figure 7). However, a larger proportion does not see a correlation between these devices and their future endeavor. This further reveals the findings in the literature that a large proportion of learners in different STEM fields then do not continue in the career path postgraduation [24].

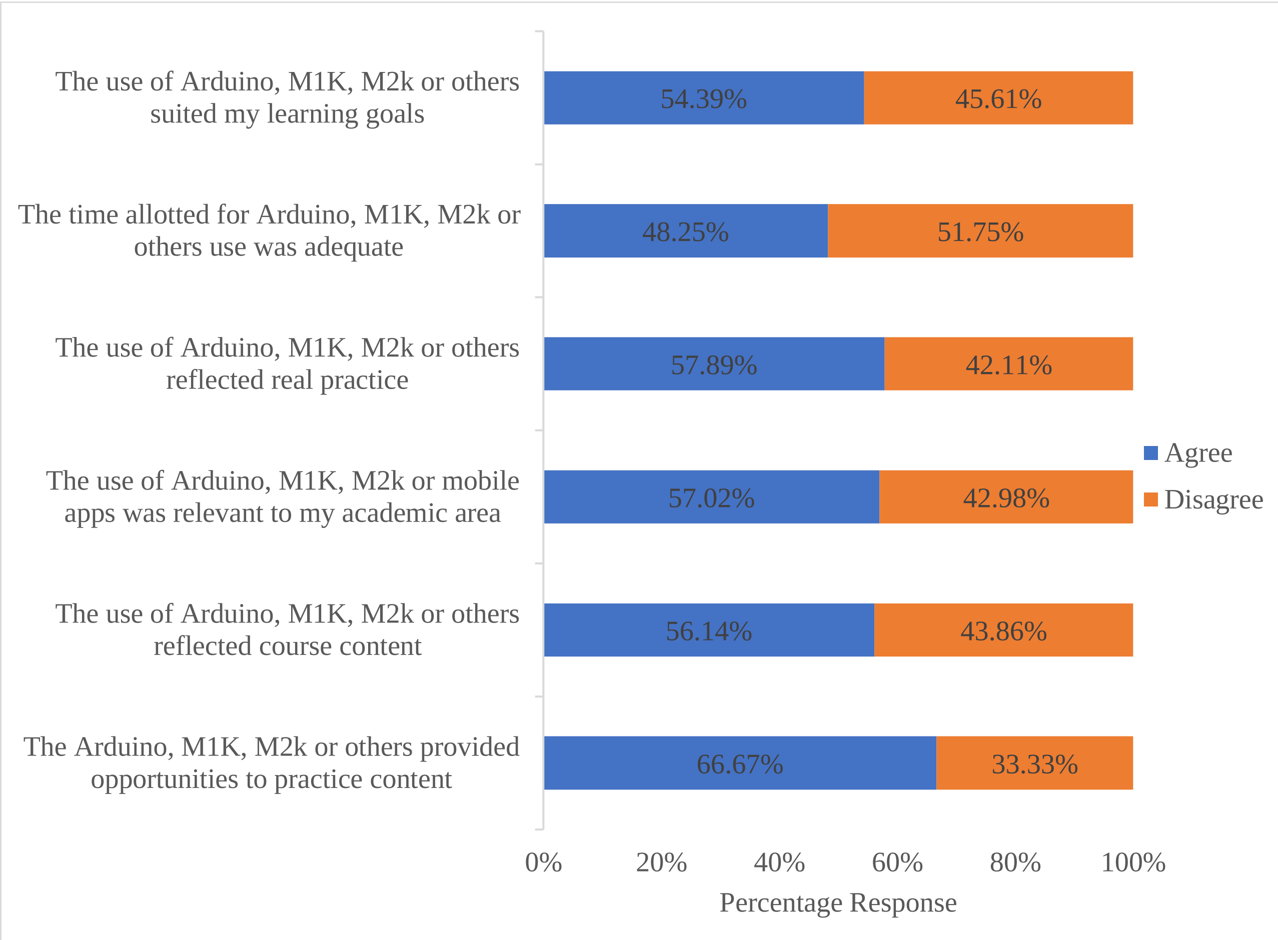


**Figure 6: Learners' Perception of the Use of Hands-on Devices**

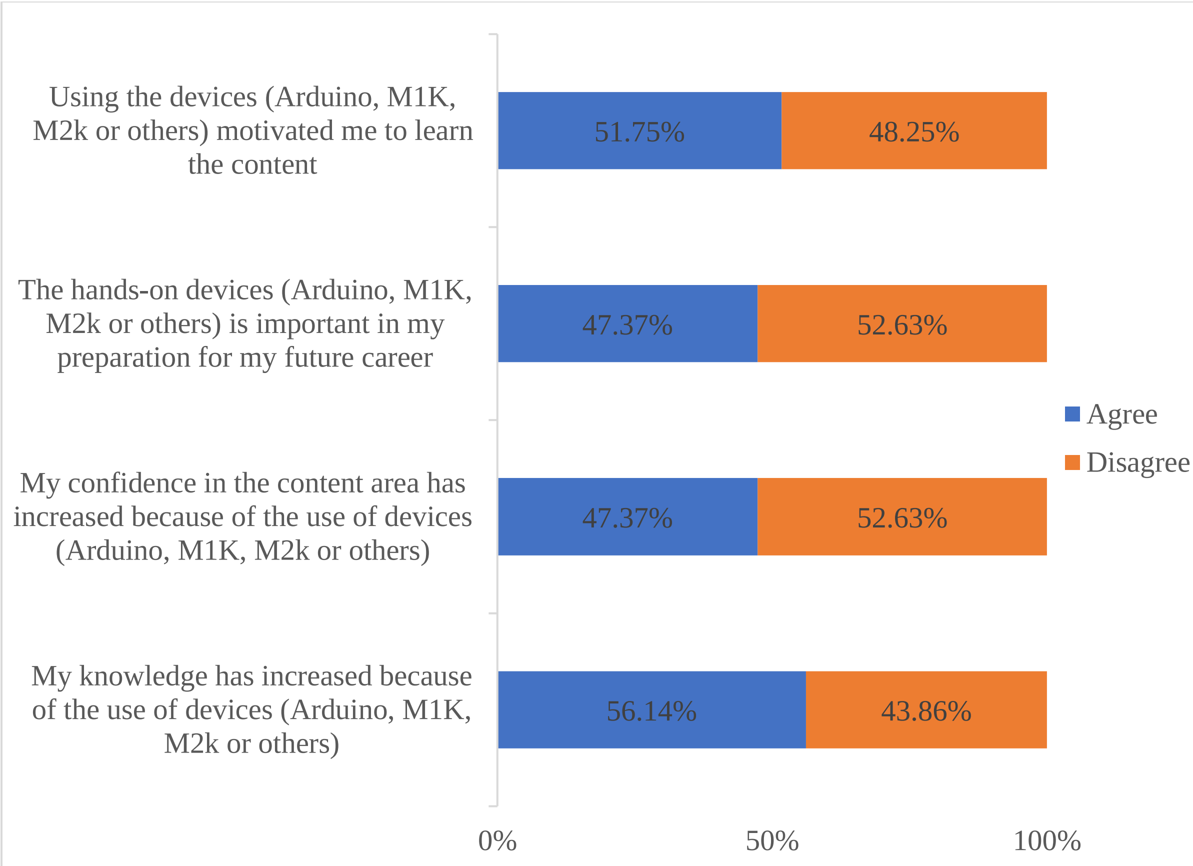


Figure 7: Learners' feedback on the use of hands-on devices

**Signature Assignment**

The students were given a signature assignment pre- and post-test on the utilization of the devices, and their performance is presented in Figure 8. The paired sample t-test showed that there was a significant difference between the pre-and post-test results. Evidently, there was a range of 0 - 66.67% improvement in the performance of the learner's post-implementation scores of the use of the devices. The comparison of the means score showed that there was a significant difference between the pre- and post-test scores ($p$<0.05). Such a significant increase in educational performance demonstrates that these devices help learners understand concepts better and lead to lasting educational gains. Similar results have been reported in the literature in Africa [25], Asia [26], and the USA [27].

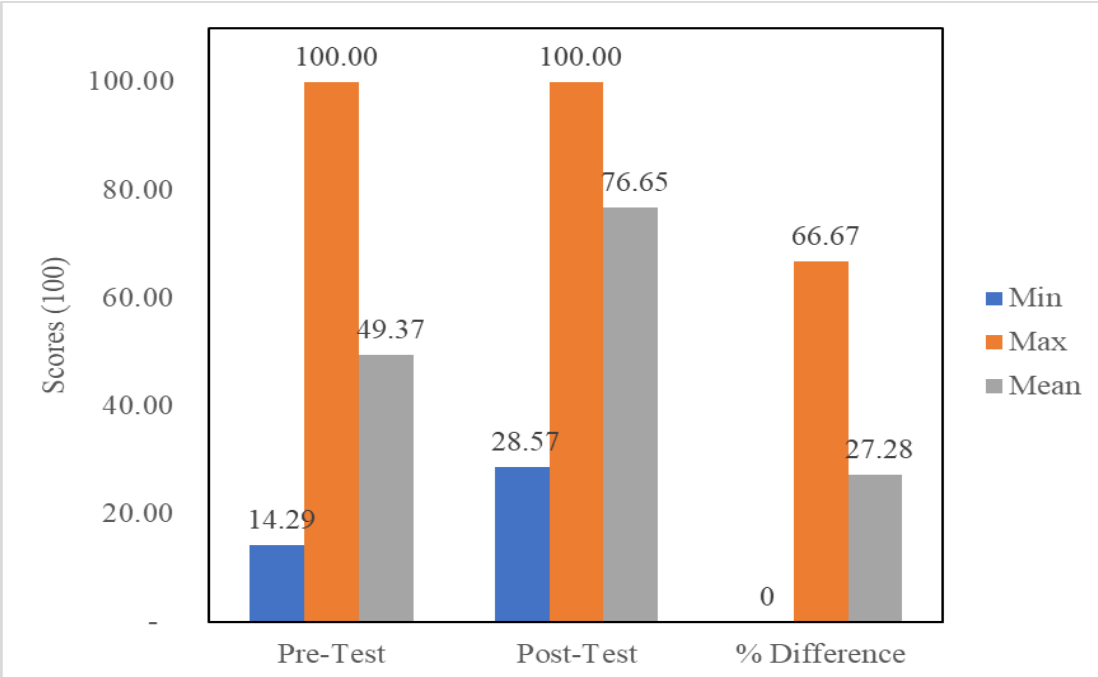


Figure 8: Signature Assessment of the Learners on Learning Concepts in STEM fields using hands-on devices ($p<0.05$)

## Conclusion

The study focused on investigating how the utilization of low-cost, easily accessible, and usable devices could improve the motivation of learners in different STEM fields and contribute to their understanding of concepts in STEM fields, leading to improved performance.

Using the inquiry-based learning framework, experiment-centric pedagogy affords an integration of technological devices into classroom learning that does not require a specialized laboratory for conducting such experiments. The study adopted a survey and assessment methodology for data collection. Data were collected pre-and post-implementation of the module in the course where it was implemented. The study found that there was a significant improvement in learners' peer learning and collaboration, as well as critical thinking. The test anxiety of the learners was also improved. The performance of the learners was also found to increase significantly. The study was limited to some courses taken at different levels of learning in different fields to avoid more than one dosage of the implementation among the learners. In addition, the completion of survey questionnaires was encouraged to ensure honest and fair participation of all learners in the course, and it was found that not all learners in the class completed both levels of evaluation and surveys. In summary, the utilization of inexpensive, safe, portable electronic devices supported learning in STEM fields and improved learners’ motivation as well as their performance in the courses.

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