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Arduino-Based Experiments: Leveraging Engineering Design and Scientific Inquiry in STEM Lessons

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Abstract

Organizing STEM activities based on scientific inquiry and engineering design processes is recommended for competency-based education in many countries, including Vietnam, to develop vital 21st-century practices. However, one of the challenges in the scientific inquiry process is the lack of equipment for conducting experiments. Therefore, there is a need for cost-effective and flexible instrument initiatives that students and teachers can design, create, and operate on their own. Additionally, real-world contexts like designing experiments for studying are also essential to engage students in engineering design processes. With its open-source platform, user-friendly interface, and limitless creative potential, Arduino is a valuable tool for STEM education. Hence, this study aims to develop Arduino-based experiments and suitable lesson plans to facilitate the implementation of STEM lessons following scientific inquiry and engineering design processes. In this study, we have proposed three Arduino-based experiments, followed by instruction plans, that students can build through engineering design processes to study several Physics concepts. The results show that microcontroller systems combined with common sensors are a low-cost yet effective approach with acceptable accuracy, allowing students to quantitatively and professionally investigate the relationship between physical quantities. In addition, 21st-century practices such as STEM literacy and design thinking are also concentrated in the context of working with the solutions for STEM problems.

Keywords: STEM classroom, Engineering design, Scientific Inquiry, Arduino-based experiments

INTRODUCTION

STEM, an acronym for Science, Technology, Engineering, and Mathematics, is frequently associated with strategies for advancing a nation's progress in these domains (Assefa & Rorissa, 2013; MacIsaac, 2016; Silva et al., 2020). In the context of education, the reference to STEM underscores the education system's concentration on Science, Technology, Engineering, and Mathematics disciplines by highlighting the incorporation of cross-disciplinary STEM subjects (e.g. Kelley & Knowles, 2016; Madden et al., 2013), real-life applications (e.g. Kefalis & Drigas, 2019; Nikitina & Ishchenko, 2022), as well as the enhancement of students' qualities and competencies (e.g., Fajrina et al., 2020).

According to Kennedy & Odell (2014), effective STEM education programs and curricula should embody 11 key characteristics, including two notable features: the promotion of engineering design and problem-solving and inquiry-based learning (Kennedy & Odell, 2014). In addition, the engineering design process (EDP) provides the opportunity for students to embark on scientific inquiry (SI) and open discovery (Hafiz & Ayop, 2019). On the other hand, using EDP, such as in science education, will allow the students to apply science knowledge and SI in an authentic context and learn mathematical reasoning to make decisions (Kelley & Knowles, 2016).

However, one of the challenges in the SI process is the lack of equipment for conducting experiments (Kranz et al., 2023). Therefore, there is a need for cost-effective and flexible instrument initiatives that students and teachers can design, create, and operate on their own. Furthermore, real-world contexts like designing experiments for studying are also essential to engage students in EDP.

Arduino, with its open-source platform (O'Sullivan & Igoe, 2004), user-friendly interface (Thompson, 2011), and limitless creative potential, serves as a valuable tool for STEM education (e.g. García-Tudela & Marín-Marín, 2023; Plaza et al., 2018). Regarding knowledge comprehension, research demonstrated the usefulness of Arduino and 3D printing in teaching STEM concepts in educational robotics classes (Souza & Sato, 2019). Regarding skills and competencies, it was found that integrating Arduino into STEM activities improved students' skills in establishing cause-effect relationships (Arı & Meço, 2021). Similarly, Vexler et al., (2022) developed an interdisciplinary course on circuit design using Arduino, which enhanced students' scientific and technological capabilities (Vexler et al., 2022). Overall, studies highlighted the potential of Arduino-based experiments for improving STEM Education.

One of the approaches involves introducing educational projects where students employ Arduino to construct products like robots and machines, thus gaining knowledge, honing their abilities, and nurturing their passion for learning (e.g., Di Giacomo & Sandri, 2022; Morze, 2018). Moreover, Arduino can be a cost-effective platform for creating devices or conducting experiments that align with the scientific inquiry processes within STEM education (e.g., Sari & Kirindi, 2019).

Building upon the mentioned information, it becomes evident that STEM-integrated lessons have the potential to cultivate students' competencies and instill 21st-century practices, viewed through the lens of EDP applied to the creation of instruments for SI. Currently, there are several studies on Arduino-based experiments in STEM Education, but the majority of them primarily employ Arduino as a teaching tool (Çoban & Erol, 2021, 2022; Galeriu et al., 2014) or a remote initiative (Cvjetković & Stanković, 2017; Martin et al., 2021) rather than delving into how it can serve as a study object in students' educational processes. Hence, this study aimed to develop Arduino-based experiments that aim to facilitate the development of 21st-century practices of students in STEM classrooms. The study goal is equivalent to the following research questions:

1. *How can Arduino-based experiments be designed to be implemented in STEM lessons for students?*
2. *How can we implement developed Arduino-based experiments to leverage Engineering Design Processes and Science Inquiry Processes in STEM lessons?*

METHOD

Developing Arduino-based experiments

To ensure that the Arduino-based experiments are customizable, under control, cost-effective, easy to maintain, and accessible for teachers and students, we based on the procedure encompassing six design principles to develop open-source hardware designs for scientific equipment proposed by Oberloier & Pearce (2018).

Firstly, we study existing experiments used to investigate Physics concepts. These experiments either involve expensive measuring instruments or need a more precise approach comparable to modern scientific measurement methods.

After that, we consider alternatives of using the Arduino board combined with sensors as measurement instruments. For example, current sensors can help to measure the power of electrical devices, or temperature sensors can replace thermometers. After that, we develop experiments, including apparatus setup, programming, and executing procedures. This design process follows design principles including:

- Open-Source Approach: Free and open-source software tool chains and open hardware are prioritized throughout fabrication, promoting accessibility and collaboration.
- Simplicity and Efficiency: Efforts are made to minimize both the number and variety of parts in the device and the complexity of the required tools, ensuring ease of assembly and maintenance.
- Resource Conservation: The design seeks to minimize material usage and production costs, promoting sustainability and cost-effectiveness.
- Digital Fabrication: Components that can be digitally manufactured using widely available tools like the 3D printer are favored, enhancing accessibility and reducing production barriers.
- Customization Capability: Parametric designs with pre-designed components are employed, allowing flexibility and customization to suit specific needs and requirements.

- Global Accessibility: Components that cannot be economically produced using existing open hardware methods are sourced from off-the-shelf parts, ensuring availability and accessibility worldwide.

Then, developed experiments are tested to verify the quality of functions, accuracy, and whether they are validated for the targeted functions.

Finally, the experiments' design, manufacture, assembly, calibration, and operation were documented and ready to be shared in the open-access literature.

Developing lesson plans

There are several approaches when designing STEM lessons, there are different approaches, including silo, embedded, and integrated (Roberts & Cantu, 2012). The silo approach involves the separation of STEM components. It is considered the most traditional, primarily focused on teacher-driven activities, often neglecting the real-world problem-solving aspect of learning (Breiner et al., 2012). Conversely, the embedded approach is well-known for emphasizing acquiring knowledge by studying real-world problems and problem-solving techniques within social, cultural, and functional contexts (Chen, 2001). Lastly, the integrated approach blurs the boundaries between individual subjects, teaching science, technology, engineering, and mathematics as a unified whole (Wang et al., 2011). In this study, in the context of organizing curriculum content based on subjects, the most suitable approach is embedded (Roberts, 2012). A STEM lesson, where teachers contain regular classroom lessons to teach subject content in a STEM approach, can be implemented using the SI and EDP processes as outlined in Figure 1. In this study, we constructed a teaching plan based on organizing learning activities that incorporate both processes.

Firstly, we assessed the compatibility of Arduino-based experiments with the learning objectives or specific knowledge units. Then, we developed an SI process for the targeted learning objectives or knowledge units, starting from the phases of problem definition, idea development, planning, problem-solving, and drawing conclusions. In this SI process, Arduino-based experiments were used during the problem-solving phase for students to investigate or verify scientific hypotheses. Constructing these experiments required students to follow the EDP, beginning with defining the product, developing ideas, planning, and moving on to designing and presenting solutions.

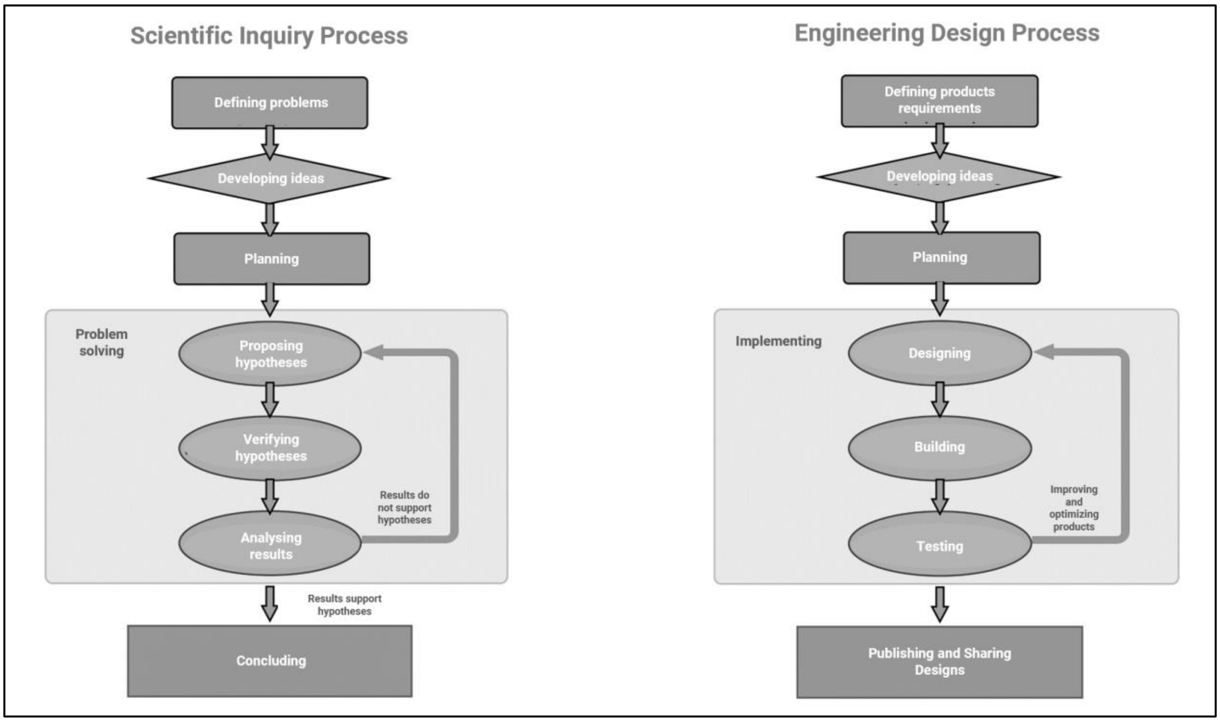

Figure 1. STEM learning activities following SI and EDP

RESULTS AND DISCUSSION

Arduino-based experiments

Following the mentioned steps, we have proposed three Arduino-based experiments.

Determining the specific capacity of liquids

The setup of our Arduino-based experiment to determine the specific capacity of liquids (Figure 2) includes a calorimeter with a heating resistor, a DS18B20 temperature sensor, an ACS712-20A current sensor, a DC voltage sensor module (0-25V), and an Arduino Uno to read sensor values and transmit them to computer software. The wiring connections of these sensors are depicted in Figure 2. The experiment can be powered by a 12V battery system or a DC power supply to operate the equipment and monitor sensor values through computer software.

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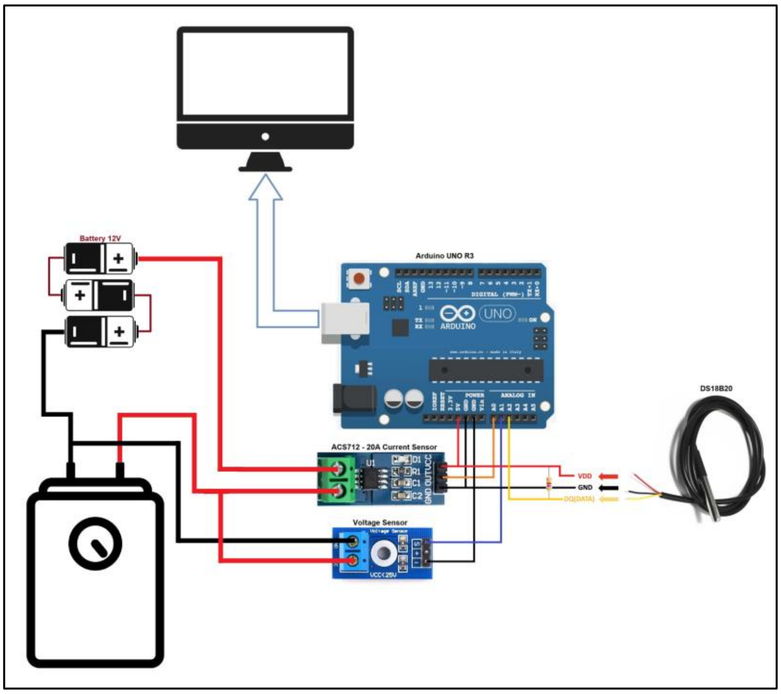

Figure2. Set up an Arduino-based experiment to determine the specific capacity of liquids.

A short Arduino programming code snippet is necessary to collect experimental data. First, the computer will compile this program and then send it to the Arduino board via a USB cable. The Arduino board will execute the code and continuously send the values of the three sensors back to the computer. These values are sent to the computer every 1000 ms. The list of experimental measurements is displayed on the software interface as a table and can be saved as a Microsoft Excel spreadsheet.

The data analysis (Figure 3) initially involved extracting specific values suitable for simple calculations suitable for K-12 students. The data obtained indicates that the temperature value did not change significantly due to limitations in the smallest division of the measuring device; the energy varied continuously. Therefore, the energy value at a given temperature can be calculated as the average of the maximum and minimum energy values. This analytical approach yielded the specific heat capacity of water, ranging from 3970 J/kg.K to 4379 J/kg.K, which deviates by a maximum of 5.11% from the theoretical value of 4184 J/kg.K. Further analysis utilized Origin 2021, a robust software application designed specifically for scientific computations. We employed a fitting function, which yielded the specific heat capacity of water as about 4183 J/kg.K. The R-square value is remarkably close to one, providing additional evidence that the linear model accurately describes the experimental data.

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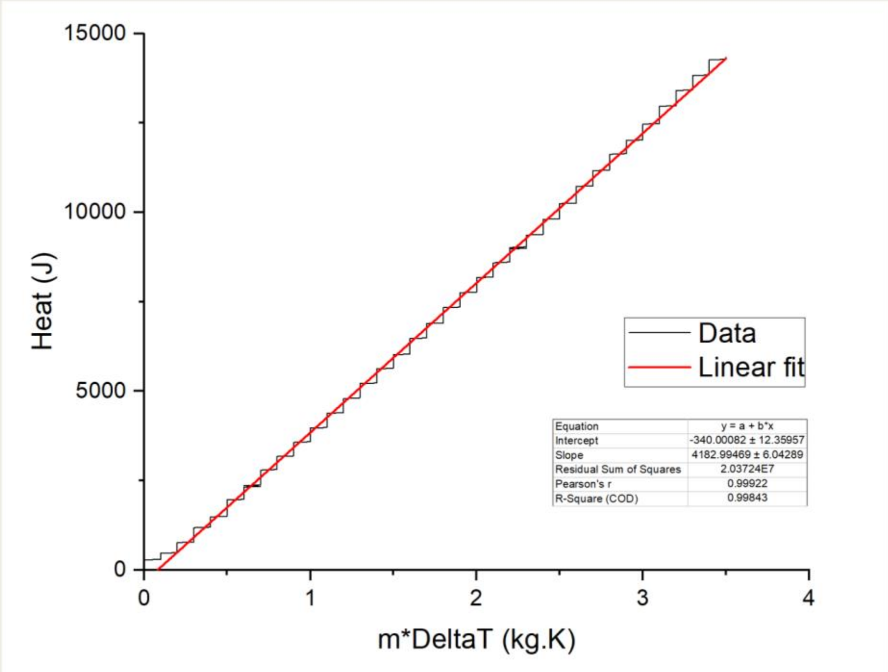
No.	Change in Temperature (°C)	Change in Energy (J)	The specific heat capacity of water (J/kg.K)	Compared to 4184 J/kg.K (%)
1	38-33	4599.0-629.0	3970.0	5.11
2	43-38	8813.5-4599.0	4214.5	0.72
3	48-43	13192.5-8813.5	4379.0	4.66

Data Analysis Method 1



Data Analysis Method 2

Figure 3. Data analysis of Arduino-based experiment to determine the specific capacity of water.

Verifying the law of conservation of momentum

In this Arduino-based experiment (Figure 4), we employed Arduino Uno and Doppler Radar to determine the velocity of an object. The HB100X10.525GHz obstacle sensor is a Doppler module operating in the X-band. It includes a dielectric resonator oscillator (DRO) integrated with antennas for signal transmission and reception. The sensor emits a 10.525GHz signal with a range of up to 20 meters. Notably, this sensor's operation is unaffected by external factors such as noise and humidity and is designed to resist strong radio frequency interference.

Additionally, the module incorporates amplification and comparison circuits using the LM6482 IC to improve data acquisition accuracy. During experiments, an ultrasonic sensor was also utilized to detect collision between two carts. In this setup, distance and Doppler radar sensors were placed at either end of the experiment. The Doppler radar read the velocity of cart A throughout the investigation. At the same time, the distance sensor emitted pulses to measure the distance of cart B, facilitating the separation of data before and after the collision. Before the collision, as the distance remained constant, the velocity before the collision was calculated and displayed on the screen. When the two carts collided and moved toward the distance sensor (resulting in decreased B's distance), the post-collision velocity was calculated and displayed on the screen.

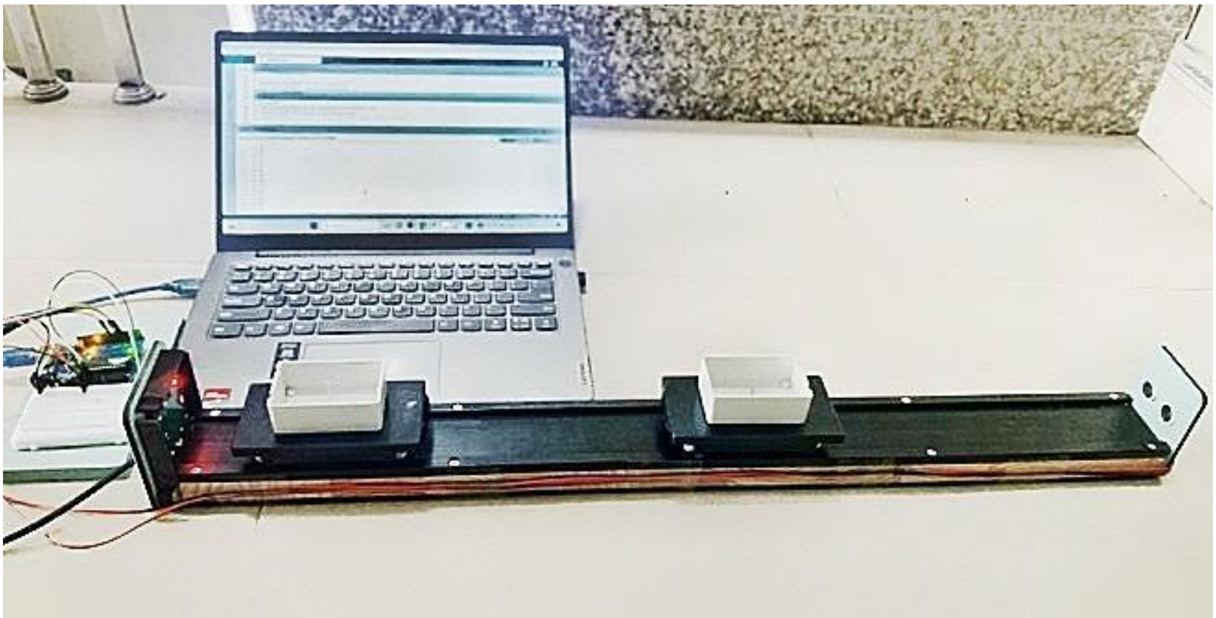


Figure 4. Set up an Arduino-based experiment to verify the law of conservation of momentum.

Throughout these experiments, only the velocities immediately before and after the collision were observed, effectively assuming the system was a closed system. Momentum calculations were performed for each measurement (Figure 5). In the first measurement, with both A and B having a mass of 0.1 kg, the post-collision momentum of the system differed by less than 1.33% from the pre-collision momentum. In the second measurement, where A's mass was increased to 0.15 kg by adding a 50g weight, the post-collision momentum differed by less than 11.29% from the pre-collision momentum. In the third measurement, with A's mass increased to 0.15 kg and B's mass at 0.1 kg, the post-collision momentum differed within the range of 3 - 11.11% from the pre-collision momentum.

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Attempt	m_1 (kg)	v (m/s)	P (kg.m/s)	m_2 (kg)	m' (kg)	v'(m/s)	P' (kg.m/s)	Deviation (%)
m_1=m_2=0.1kg								
1	0.1	0.54	0.054	0.1	0.2	0.27	0.054	0
2		0.75	0.075			0.37	0.074	1
3		0.59	0.059			0.30	0.060	1
m_1=0.1 kg; m_2=0.15 kg								
1	0.1	0.60	0.060	0.15	0.25	0.24	0.060	0
2		0.62	0.062			0.22	0.055	11
3		0.55	0.055			0.23	0.058	5
m_1=0.15 kg; m_2=0.1 kg								
1	0.15	0.55	0.083	0.1	0.25	0.32	0.080	4
2		0.47	0.071			0.28	0.070	1
3		0.30	0.045			0.16	0.040	11

Figure 5. Data analysis of Arduino-based experiment to verify the law of conservation of momentum.

Compared to traditional experiments measuring velocity using optical gate barriers, where the obtained velocity represents the average velocity of the cart during the light barrier activation period, this approach reduces significant experimental errors attributed to energy loss due to friction. The analysis and data acquired from the sensors align well with verifying the conservation of momentum law and K-12 students' comprehension.

Investigating the light interference phenomenon

The experimental setup (Figure 6) includes the following components. The light source is a red laser with a wavelength (λ) range of 630 - 670nm. A distance of a=0.8mm separates two slits. To collect data and control the system, we use an Arduino Uno. Light intensity data is collected using the BH1750FVI, a digital ambient light sensor that communicates via I2C. This sensor has a wide operating range with high resolution (1 - 65535lx), providing high accuracy.

Additionally, the sensor has low power consumption due to its auto-power-off feature. With this sensor, there's no need for an additional resistor as they are already pull-up resistors on the Arduino board connected to the 3.3V output, reducing complexity in the experiment setup. A Stepper Motor and its accompanying A4988 Driver, powered by a 12V supply, are used to support the movement of the BH1750FVI light sensor to different measurement positions.

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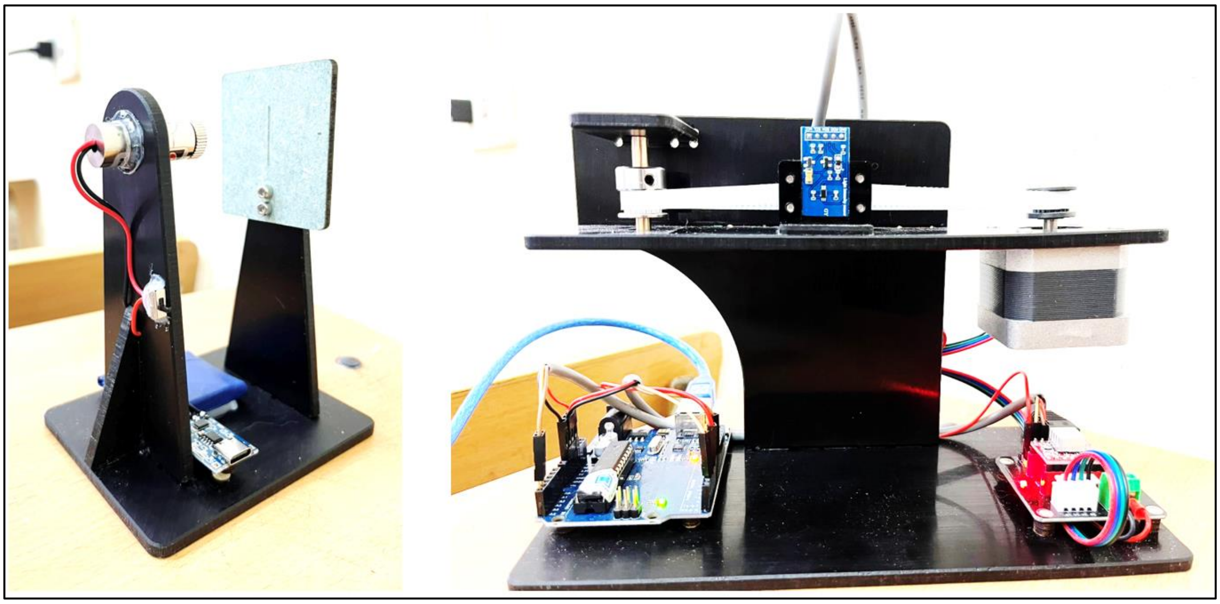

Figure 6. Setup of Arduino-based experiment to study the light interference phenomenon.

The system with two slits splits the light source (S) into two sources (F1 and F2) with the same wavelength and in-phase, with a constant phase difference over time. The light from sources F1 and F2, when they converge at various positions (x), creates an interference pattern. The 12V power supply powers the stepper motor and its driver. The stepper motor rotates in small increments ($\Delta\varphi = 1.8^o/32 = \pi/320$ radians) with a diameter of the rotating shaft (d) being 12mm. This rotation results in the linear movement of the conveyor in discrete steps (Δx). The light sensor is attached to the conveyor and, controlled by the stepper motor, the sensor moves a small distance (Δx) within a short time interval (Δt). This allows for measuring light intensity (I) at corresponding positions (x). The obtained data provides interference patterns to be calculated and applied in various problem-solving scenarios.

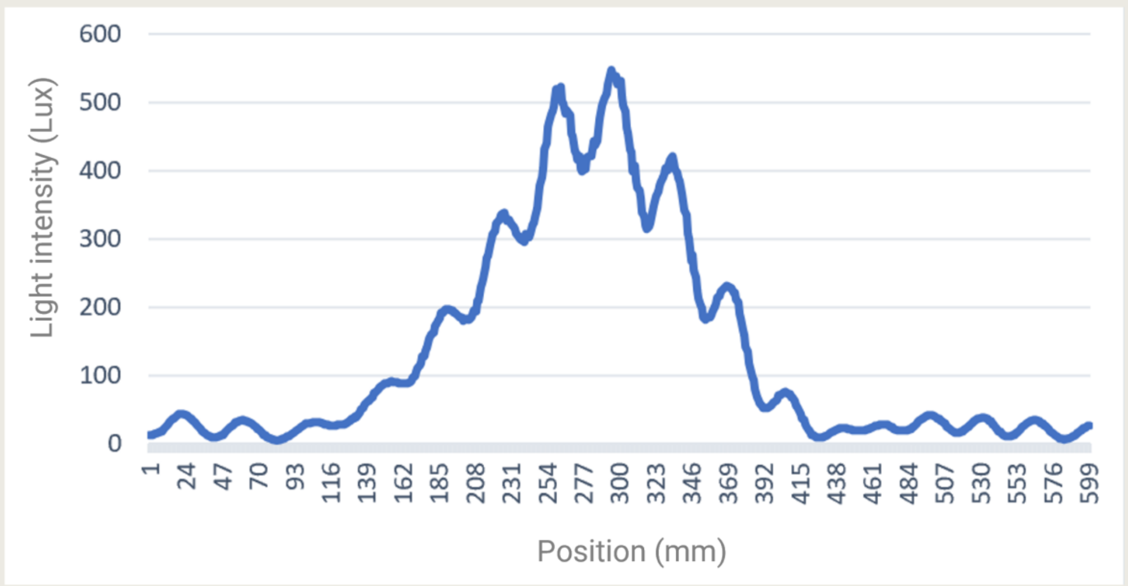

Figure 7. The graph of light intensity regarding position.

According to the theory, the dark fringes in interference patterns should have zero light intensity. However, the measured experimental graph (Figure 7) shows non-zero values for these dark fringes because the sensor calculates the average light intensity over the entire sensor area instead of at a specific position. The experimental graph also exhibits discrepancies when compared to the theory due to other factors such as environmental influences or light scattering. Nevertheless, the obtained results clearly illustrate the rise and fall of the graph, explaining the formation of bright and dark fringes on the screen.

Based on the graph of light intensity obtained, we can calculate the fringe width (i), the distance between two consecutive bright or dark fringes. From the graph, we can calculate the fringe width as follows: $i = n.\Delta x = 40.\ \Delta\varphi.r = 40.\Delta\varphi.d/2 = 40.(\pi/320).6.10^{-3} = 2{,}35.10^{-3}$(m). The LED used has a wavelength in the range of 640nm - 760nm, the distance from the slits to the screen is approximately 1.55 meters, and the separation distance between the two slits is 0.5 millimeters. Theoretically, the screen's fringe width (i) should be between 1.92 and 2.36 millimeters. Therefore, the experimental results show an error in i ranging from 4% to 18%. If we consider the experimentally determined fringe width (i) as accurate, we can reverse-calculate the precise wavelength of the laser light source to be 758.10^{-9} m.

Instruction plans.

After developing and testing Arduino-based experiments, we design equivalent instruction plans based on strategies to create engaging learning activities utilizing these experiments to leverage Engineering Design Processes and Science Inquiry Processes in STEM lessons, including activities with learning materials like worksheets and videos. These teaching plans are developed based on the two frameworks we have mentioned. In these plans, students will acquire lesson knowledge through the SI process, and the EDP will be integrated into it through activities involving the design of experiments to investigate or verify students' scientific hypotheses. Figure 8 below is an example of a lesson plan using this approach to teach about specific heat capacity.

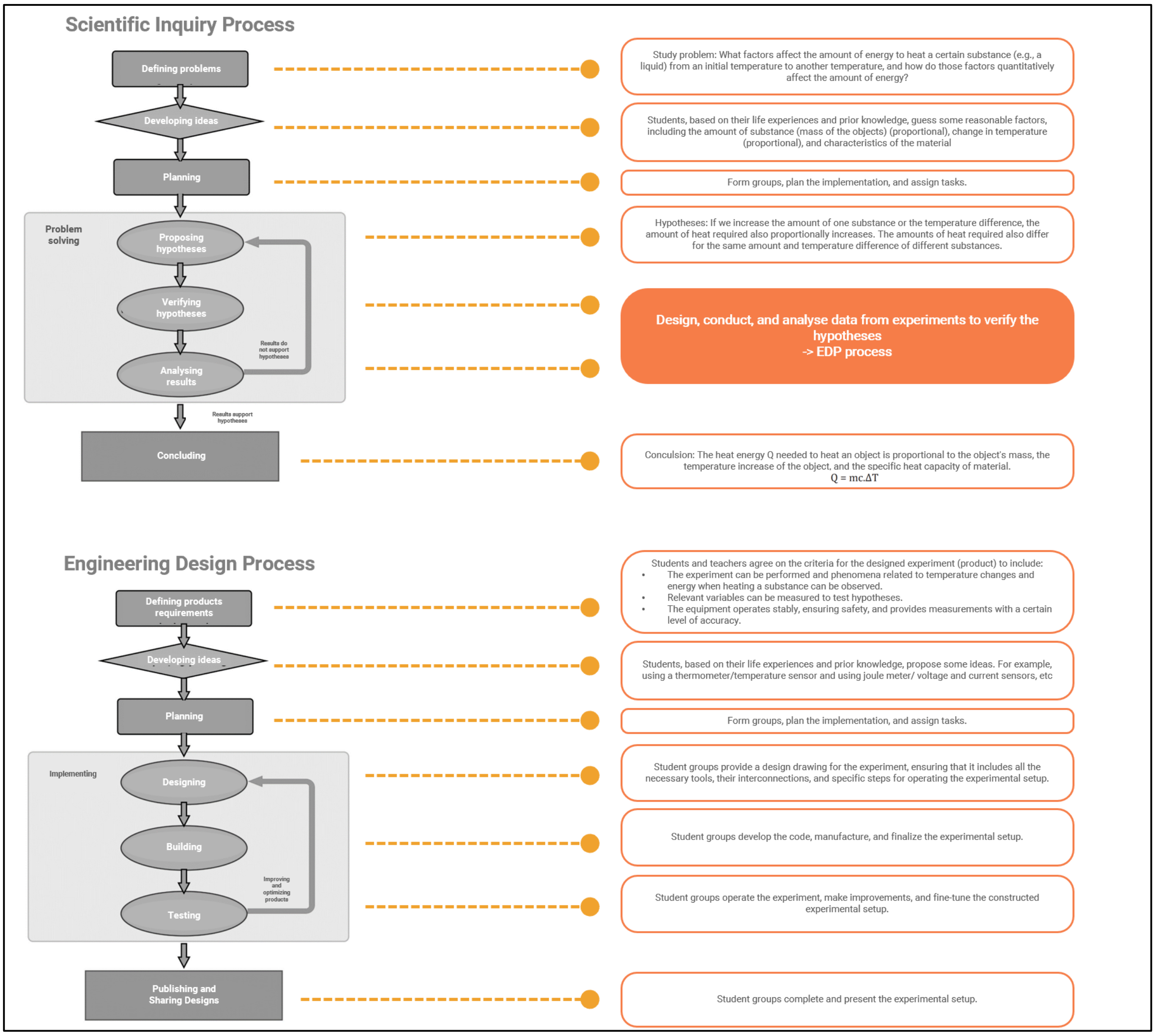

Figure 8. Teaching processes for a STEM lesson with Arduino-based experiment to study specific heat capacity

Overall, developed experiments allow the experiment to be conducted fluently and make precise measurements while ensuring the differences in the physical quantities between experimental results and the actual value are small enough to be acceptable for K12 experiments. Moreover, the total expenditure of the experimental prototype of the project is suitable for Vietnamese students. The cost can be reduced by designing the microcontroller board instead of using the Arduino board directly.

The designed lesson plans for STEM education in this study are believed to satisfy both pedagogical principles and the specific requirements of a STEM lesson because we have considered the following aspects. Effective STEM lesson plans must harmoniously integrate pedagogical principles that encourage active learning (Herreid, 2006; Srinath, 2014), differentiation (Balgan et al., 2022), and assessment (Karakaya & Yılmaz, 2022; Potter et al., 2017). Furthermore, these STEM lesson plans should captivate students through hands-on activities (Cloutier et al., 2016; Wysocki et al., 2013) aligned with learning objectives to promote inquiry-based learning while connecting classroom knowledge to real-world applications (Rennie et al., 2017). Additionally, a STEM lesson plan should emphasize interdisciplinary collaboration and developing 21st-century skills (Fajrina et al., 2020), ensuring that students acquire subject knowledge and the skills and mindset necessary for success in STEM fields and beyond.

CONCLUSION

In this study, we have proposed Arduino-based experiments, followed by instruction plans, that students can carry out to study several Physics concepts. Those experiments have acceptable degrees of accuracy, and the instruction plans have the potential to develop students' practices.

Limitations of the research

Despite having developed Arduino-based experiments and lesson plans based on STEM teaching organization principles, additional intervention research is still needed to investigate the effectiveness of these impacts on students. Subsequent studies may incorporate these lesson plans into real classroom settings or apply these Arduino-based experiments to other learning activities.

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