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Resolution of Light Transmission via Arduino-Based STEM Education Material

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Abstract

This study reports a basic experimental procedure to measure light transmission through some transparent materials through Arduino microprocessors. The basic experimental material is made up of materials used daily by elementary students, and the procedure is very simple and can surely be employed for teaching activities as STEM education material. The STEM material particularly focuses on transmission rates as a function of the thickness of the material. The absorption rates are experimentally measured using a specially designed box with two separated parts with a small window and an Arduino Uno microprocessor connected to an appropriate light detector structured as STEM education material. The experimental resolutions are managed for two materials, namely blue acetate and red acetate, with different thicknesses. The absorption coefficients are found to be 2.89 mm^{-1} for blue acetate and 1.54 mm^{-1} for red acetate. This work offers inexpensive teaching material that can create an education environment where students can feel dynamic and encompass the acquisitions of Science, Technology, Engineering, and Mathematics.

Keywords: Physics education research, light transmission, transmission coefficient, STEM education, Arduino.

INTRODUCTION

Physics deals with any phenomena, including energy or matter, and tries to resolve natural laws and develop theories that can predict the results of experiments (Serway & Jewett, 2008). Therefore, physics is commonly considered to be problematic due to encompassing complicated concepts and natural events. The difficulty also arises from the necessity that any theoretical formulation has to be firmly verified by the experimental outcomes. Hence lack of adequate and simple experiments in general creates great problems in teaching processes (Veloo, Nor, & Khalid, 2015; Bierlich et al., 2020; Vilia & Candeias, 2020). Consequently, physics education research targets to identify topics that students experience learning difficulties and try to reduce complications by developing appropriate and simple experiments to verify the related theory (Wieman & Perkins, 2005; Maknun, 2020; Kuzmenko, Dembitska, Miastkovska, Savchenko, & Demianenko., 2023).

The interaction of light with matter is an important and complicated topic of physics taught in the physics curriculum at both undergraduate and secondary education levels. The topic is naturally difficult because depending on the energy level of the light and the properties of specific matter, there can be various mechanisms occurring, namely reflection, absorption, or transmission. The reflection mechanism occurs from the material's surface by mainly elastic scattering of light. Inelastic scattering of the light by electrons or atoms of the material, in general, causes the absorption. Inelastic scattering has several options, namely Compton scattering, photoelectric effect, or thermal heating. Absorption of light makes a substance dark or opaque to the wavelengths or colors of the incident wave. All those mechanisms causing the absorption of the light result in light energy transformation to other energy types and consequently result in a decrease in the transmission of the light. Therefore, the transmittance of materials directly determines the absorbance, which, in fact, enlightens certain properties of matter. The light transmittance of materials formulated by Beer-Lambert law and experimental verification of the law is obviously very important for comprehensive learning of the absorption or transmittance of light. There are some recent studies focusing on teaching the Beer-Lambert law. A recent effort has designed and reported a method to teach how light absorption depends on the absorbing medium's thickness. This teaching experiment is specifically characterized as bringing to bear a ‘concept-driven interactive pathway’ (Viennot & de Hosson, 2015;dos Santos et al., 2023). Arduino learning helps students and educators engage with digital content (Sulimro, Santoso, Josephine, Prabowo, & Gading, 2023). Another recent effort proposed the use of a smartphone-based apparatus as a valuable tool for investigating the optical absorption of material and verifying the exponential decay predicted by Beer’s law. This experimental approach is suitable for undergraduate students and allows one to measure the material transmittance, including its dependence on the incident radiation wavelength (Onorato, Gratton, Polesello, Salmoiraghi, & Oss, 2018). Recent work has demonstrated the use of smartphones in an experiment on light absorption and light scattering. The LED display and smartphone camera are used as the light source and as the detector, respectively. The color wheel is used to choose the color of the light source to be shone through the sample for analysis (Malisorn, et al., 2020). The Beer-Lambert law is lately verified by using the Phyphox application of smartphones, emphasizing the integrated content approach, as knowledge of physics, mathematics, and computing is simultaneously needed in order to confront the physics experiments (Colţ, Radu, Toma, Miron, & Antohe, 2020;.Schouten, Parisi, & Downs, 2009)

The STEM education method is one of the latest and trendy educational methods used for physics education. STEM education is based on an interdisciplinary education process in which the achievements of Science, Technology, Engineering, and Mathematics are included. Engaging students in high-quality STEM education requires that programs include a rigorous curriculum, instruction, and assessment, integrate technology and engineering into the science and mathematics curriculum, and encourage scientific inquiry and the engineering design process. Recently, numerous studies have focused on STEM education and reported on a number of topics pointing out the importance and popularity of the approach (Seyranian et al., 2018). On the other hand, Arduino microprocessors are devices that include digital and analog sensors, LEDs, motors and heating elements, where sensors and transducers are widely available. Arduino microprocessors are used at almost every level of education, technology, and engineering. Arduino microcontrollers are electronic devices that can be programmed with C language and collect data from various sensors with the help of these electronic devices, where very good work can be done with the introduction of robotic coding (Petry, Pacheco, Lohmann, Correa, & Moura, 2016; Çoban & Erol, 2022).The importance of Arduino use in physics education is rapidly increasing due to being inexpensive, easy to apply, and coded by C language that is easy and is globally available open source. For this reason, measurement tools and experimental setups can be designed with the Arduino microcontrollers and can easily be employed in physics experiments. Numerous recent studies are reporting the use of Arduino in measuring and teaching various sub-fields of physics education, namely mechanics (Çoban & Erol, 2022; Erol & Oğur, 2023), electricity (Zachariadou, Yiasemides, & Trougkakos 2012), magnetism (Atkin, 2016), optics (Gopalakrishnan & Gühr, 2015), thermodynamics (Prasitpong, Phayphung, & Rakkapao, 2023).

The aim of this study is to verify and teach light transmission through some transparent materials, such as Arduino-based STEM education materials. This work is particularly useful in using low-cost instruments and requiring basic knowledge of electronics in a STEM application.

THEORY OF BEER-LAMBERT LAW

The interaction of light with matter has been an important topic of physics for centuries. The first preliminary studies were managed by Bouguer, who focused on astronomical phenomena and tried to resolve the attenuation of light passing through the matter. However, the mathematical formulation based on Bouguer's studies was carried out by Lambert. Later, the problem was tackled by Beer, who worked on chemical solutions (Di Capua et al., 2014).

The interaction of light with the matter in fact contain very complicated processes and can be handled by both classical and quantum mechanical approaches. The theoretical resolution in this case will be the classical one for the simplicity. The intensity of an electromagnetic wave can be formulated in terms of both electric field or magnetic field or both. The time average energy flux which is the intensity of an electromagnetic field can be formulated by, $I = \frac{E_0^2}{2\,\mu_0\,c} = \frac{c\,\varepsilon_0\,E_0^2}{2}$ or alternatively, $I = \frac{c\,B_0^2}{2\,\mu_0} = \frac{c^3\varepsilon_0\,B_0^2}{2}$. In this formulations, E_0 denotes the amplitude of the electric field, B_0 denotes the amplitude of the magnetic field, c denotes the speed of the light, μ_0 denotes the magnetic permittivity of the free space and ε_0 denotes the dielectric permittivity of the free space.

Light or electromagnetic waves entering a material obviously interact with the atoms of the material, and any inelastic scattering results in energy transfer to the atoms and, therefore, the energy of the electromagnetic wave and, therefore, the intensity of the light decreases, resulting attenuation. This interaction can be formulated by (Spitha et al., 2021;Echevarria & Hernandez, 2013)

$$dI = -\mu\, I\, dx \tag{1}$$

where μ denotes the linear attenuation coefficient, I is the intensity, dx denotes the infinitesimal distance the light travels and dI represents the relevant intensity change. Integrating this equation from I_0 to *I* and the distance from 0 to x leads to the equation of,

$$I = I_0\, e^{-\mu\, x} \tag{2}$$

In this equation the linear attenuation coefficient mainly depends on two parameters, firstly wave length dependent absorption coefficient $\sigma(\lambda)$ and molar concentration of the material, $c = \frac{N}{N_A\,V}$, and the relation can be formulated as $\mu = \sigma(\lambda)c$. (Abitan et al., 2008) It is obvious that the linear attenuation coefficient also depends on the wavelength of the light, so $\mu = \mu(\lambda)$. The transmittance of the material is defined as, $T = \frac{I}{I_0}$ and it is straightforward to get the expression of,

$$ln\,\frac{I}{I_0} = -\mu\, x \tag{3}$$

Hence one can plot natural logarithm of the transmittance as a function of distance to determine the linear attenuation coefficient of, μ. If the structure of the matter is known so the molar concentration then it is possible to estimate the attenuation coefficient of the material. The absorbance of the material can be defined as $A = \frac{I_0 - I}{I_0}$ and in any case $A + T = 1$ ought to be verified.

METHOD

Experimental Setup

The experimental setup consists of a computer with the appropriate code installed, two 9V battery-powered LED white light sources, numerous red and blue acetates, an Arduino Uno microprocessor, two LDR (Light Dependent Resistor) 5mm sensors, a breadboard, an Arduino Uno-computer communication cable, various connection cables and most importantly a specially designed closed black box. The experimental setup, including all the equipment, is shown in Figure 1.

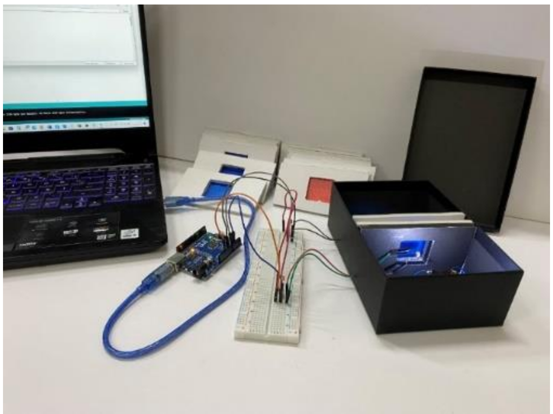

Figure 1. Photo of the experimental setup, including all the parts employed for the measurements.

The black box is specially designed to be separated by cardboard with a small window in the center to place the materials with various thicknesses. The black box also has a stiff cover to prevent light from penetrating the box during the measurements. The box has tiny holes where the communication cables connect the LDR light sensor and the Arduino microprocessor. The experimental measurements were carried out on two materials, blue acetate, and red acetate, with different thicknesses.

The actual data are collected by placing two LDR sensors next to the acetate, specifically one on the front side and the other behind the acetate, so that one can read the incident light intensity, I_0, and the other can read the transmitted light intensity, I. The actual data is then analyzed by calculating the transmission ratio, I/I_0, by means of EXCEL and plotting the transmission ratio as a function of the thickness of the acetate.

Arduino and Light Sensor

It is well known that the Arduino microprocessors are employed for numerous applications with the relevant sensors to collect the data and the necessary code. In this case, the Arduino Uno microprocessor is used, and the researchers wrote the necessary code for the use of the LDR light sensor. The LDR light sensor is an automatic light sensor that changes its resistance depending on the light level it receives. The LDR light sensor is circular and 5mm in diameter. LDR is made of "cadmium sulfide" (CdS), a semiconductor material that can absorb light photons. In high light, the resistance of the LDR is minimized; in darkness, it is maximized. The resistors used for communication between Arduino and the Light sensor are 1 kΩ and 220 Ω. In the circuit, 1 kΩ is used in the voltage divider with the LDR for general light sensitivity, and 220 Ω is used as a current-limiting resistor for an LDR in the same circuit. The schematic representation detailing the connections between the LDR light sensor and the Arduino Uno device is shown in Figure 2.

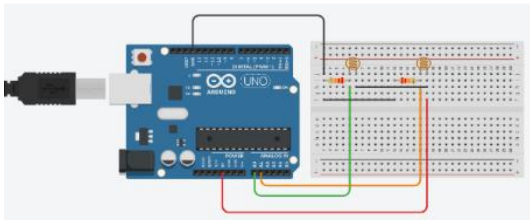

Figure 2. Schematic representation showing the details of the connections between the LDR light sensor and the Arduino Uno.

In this circuit design, two LDR sensors are used to collect data concerning the incident light intensity and transmitted light intensity.

The Code

The custom code for the LDR light sensor was written in such a way that any researcher could use it, and the actual code is presented below.

```
int value1;
int value2;
void setup()
{
Serial.begin(9600);
pinMode(A0, INPUT);
pinMode(A1,INPUT);
}
void loop()
{
```

```
value1 = analogRead(A0);
value2 = analogRead(A1);
Serial.print(value1);
Serial.print("  ");
Serial.println(value2);
delay(2000);
}
```

RESULT AND DISCUSSION

Results for Red Acetate

Ordinary office acetate paper is used in this part of the experimental procedure. Acetate paper is a transparent material that is made by reacting cellulose with acetic acid in the presence of sulfuric acid. This nonflammable, mildew-proof material is easy to dye and is available in many colors. It is inexpensive and easy to cut with a craft knife or scissors. The measurements are managed by basically placing the LEDs and one of the light sensors in one of the sections of the box and the other sensor in the other section. The overall thickness of the material is varied by changing the number of acetate papers at the window to the same size and thickness. The thickness of a single-layer of acetate paper was measured by a micrometer as 0.088 mm. The ratio of transmitted intensity I to the incoming intensity I_0 is plotted as a function of the thickness of the material given in Figure 3.

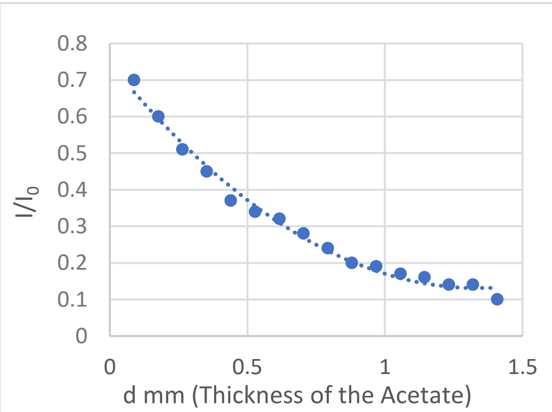

Figure 3. The graph showing transmittance, $T = \frac{I}{I_0}$, versus the thickness of the material, d; for the red acetate. The thicknesses of the acetates are measured by ordinary micrometers.

As expected, the figure shows a clear exponential decrease, in harmony with the theoretical formulation given in equation (2). To estimate the actual linear attenuation coefficient for the red acetate paper, the natural logarithm of the intensity transmittance is plotted as a function of the material thickness in Figure 4.

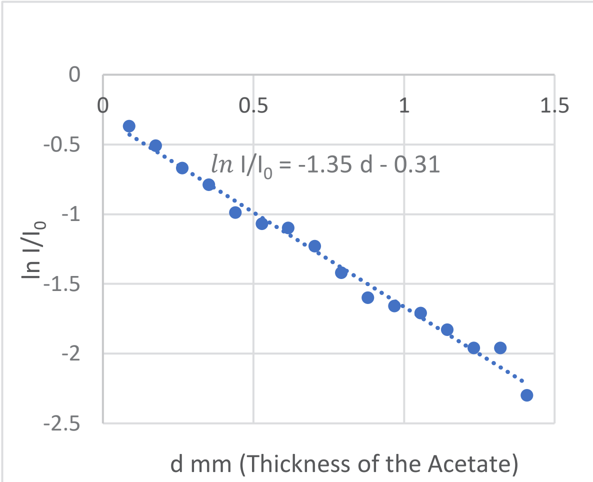

Figure 4. The graph showing the natural logarithm of the transmittance, $ln\frac{I}{I_0}$, versus the thickness of the material, d; for the red acetate.

The plot obviously shows a clear linear relation. The mathematical formulation for the linear relation is estimated to be, $ln\ \frac{I}{I_0} = -1.35\ d - 0.31$ which yields to the linear attenuation coefficient of $\mu(\lambda) = 1.35\ mm^{-1}$. This mathematical relation can be confirmed by taking the thickness of the material nought, d=0, which represents the case that no material exists between the two LDR detectors, hence $T = \frac{I}{I_0} = 1$ and consequently $ln\ \frac{I}{I_0} = 0$ ought to be verified. In our measurement the last figure of the mathematical model is 0.3 which is very close to nought, confirming the reliability of the method. In this case, the white light LED generates electromagnetic waves ranging approximately from 365nm up to 450nm. The electromagnetic waves or the relevant photons with different wavelengths obviously interact with the atomic structure of the acetate paper and depending on the specific mechanism, some of them are absorbed whereas some are transmitted. The linear attenuation coefficient measured represents the overall transmitting intensity covering all wavelengths. In the theoretical section, it was expressed that the linear attenuation coefficient is wavelength dependent and defined by $\mu(\lambda) = \sigma(\lambda)c$. The wavelength dependence cannot obviously be resolved with this experimental design however the exponential decrease of the transmittance can clearly be resolved for teaching purposes.

Results for Blue Acetate

The same procedure is applied for the blue acetate and the ratio of the transmitting intensity to the incoming intensity is plotted as a function of the material thickness. The graph is given in the Figure 5.

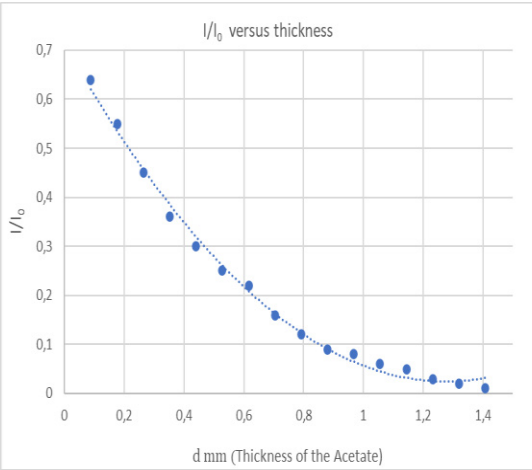

Figure 5. The graph showing transmittance, the thickness of the material, d versus $T = \frac{I}{I_0}$, for the blue acetate.

The graph clearly demonstrates the exponential decrease in the transmission of light as the thickness of the material increases. This experimental result again verifies the theoretical predictions that equation (2) gave. Similarly, to estimate the actual linear attenuation coefficient for the blue acetate, the natural logarithm of the intensity transmittance is plotted as a function of the material thickness in Figure 6.

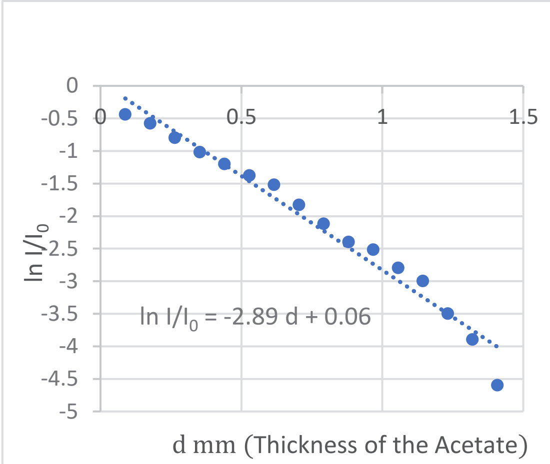

Figure 6. The graph showing the natural logarithm of the transmittance, $ln\frac{I}{I_0}$, versus the thickness of the material, d; for the blue acetate.

The plot obviously and as expected shows a clear linear relation. The mathematical formulation for the linear relation is estimated to be, $ln\ \frac{I}{I_0} = -2.89\ d - 0.06$ which yields the linear attenuation coefficient $\mu(\lambda) = 2.89\ mm^{-1}$. The last figure of the mathematical equation, 0.06, which ought to be nought for d=0 and very close to zero, demonstrates the reliability of the experimental apparatus, the procedure and the method.

CONCLUSION

In this work, an alternative approach is developed and reported to measure the light transmission of materials by means of a specially designed box and an Arduino microprocessor. The method is especially significant in the sense that the light transmission of the materials can be measured by means of daily used materials can be available in any laboratory. This approach is achieved by measuring and mathematically modelling the light transmission of the appropriate materials. The actual measurements, managed for red acetate and blue acetate, have exposed that the linear transmission coefficients for the measurements are as $\mu(\lambda) = 1.54\ mm^{-1}$ for red acetate and as $\mu(\lambda) = 2.89\ mm^{-1}$ for the blue acetate. This alternative method is very low-cost, easy to manage, and can be applied in any laboratory over the globe without needing any sophisticated equipment

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