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Can PhET simulate basic electronics circuits for undergraduate students?

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Abstract — PhET is one of the most powerful and impressive simulator innovations, widely used in the STEM-based learning process. Based on literature reviews, students are allowed to independently practice their skills and understanding of the material concept using this tool. PheT involves students in process competencies comprehensively and also provides a highly interactive virtual environment for STEM materials, including basic electronics, a sub-category of physics. This tool can also be easily accessed online at https://phet.colorado.edu/ or offline with a note that the user should download and install the application on a PC. An interesting question regarding this education tool is, "can PhET support basic electronics learning in Higher Education (HE)?" Numerous preliminary studies have not answered this question, which is associated with the technical aspect of the tool, because they only focused on the pedagogical aspect. Therefore, this research aims to fill this gap by exploring the capability of PhET in simulating basic electronic circuits that were commonly studied by students in HE, including Kirchoff Current Law (Kirchoof I), Kirchoff Voltage Law (Kirchoff II), Voltage Divider, Series/Parallel Resistors, Wheatstone Bridge, and Star – Delta Resistors. These circuits are simulated in two PhET products, namely, online (1.2.7) and offline (3.20) versions, with numerous setups used to compare their performances to the theoretical calculations. Finally, the answers were obtained clearly from the experimental results in the simulation environment. The result reveals that PhET (online and offline versions) meet the requirement to be used by students; PhET can be accessed freely and easily. PhET has excellent interactivity with the users and complies with the numerical analysis of the basic electronic circuits.

Keywords – Basic electronic circuits, offline, online, PhET, undergraduate students

I. Introduction

In this technological era, accessing information from various quality sources is easier. Based on the Law of the Republic of Indonesia No. 12 of 2012 concerning Higher Education, the series of knowledge systematically explored, compiled, and developed tends to adopt diverse approaches, scientific methods, and technology [1]. Practicum encompasses teaching and learning activities, which aid in training students' skills (psycho-motor aspects). However, this approach often lasts for a long time because asides from practice, it is also necessary to explain the material beforehand [2].

Furthermore, several factors can lead to a lengthy duration, such as inappropriate kits, un-preparedness which causes overlapping schedules, and uneven practicum initial abilities that lead to unbalanced completion time. The most common technical obstacle in electrical circuit practicum is usually encountered during the theoretical calculation process. Students are distracted by time, energy, and diverse thoughts to complete the obstacle [3], [4]. On the other hand, they have difficulties understanding the practiced sequences. Any tool in the form of a simulator is needed to help understand the behavior of the designed circuits. It also tends to confirm the framework or theory correctness, in line with the Law of the Republic of Indonesia No. 12 of 2012. Based on certain calculations, it was discovered that simulations help students to be prepared for practicum. They tend to have an overview of the actual practicum results or at least something similar to the numbers displayed in the simulation.

Proteus is an alternative simulator solution commonly applied in courses related to electrical circuits. The research by [5] stated that version 8 pro effectively boosts the students' potential or cognitive abilities compared to only watching learning videos. This is evidenced by the pretest and post-test results of 36.29 and 79.71, respectively [5]. Proteus offers a lot of items; therefore some novice students usually find it difficult to search for the needed ones. Like virtual laboratories, certain items, such as components and measuring devices, use symbols rather than real forms. Students are expected to memorize electronic engineering drawings.

Some other research employed alternative simulators, namely the Circuit Wizard. It helps to boost the students learning effectiveness compared to the conventional approach, which contributes relatively 25.34% [6]. The drawback of this simulator is centered on the fact that the simulation results deviate from the theoretical calculations, especially in circuit mode. In PCB mode, it provides a virtual laboratory, ensuring the components or measuring instruments are displayed by ensuring the interface is extremely interactive. Similar to Proteus, Circuit Wizard is a paid software. Therefore, not all students can freely access its features in the trial version.

An alternative simulator, which is free and provides good interactivity, is the Physical Education and Technology (PHET) application. It has two versions, offline and online, and was designed by the University of Colorado. PhET online and offline have been widely used by numerous teachers and students worldwide to enhance learning quality [7] and are even more popular during the Covid-19 pandemic period (Study-from-Home) because PhET strongly supports online practical learning on relevant topics [8]. PHET is considered the right solution to this problem.

The research by [9] showed the students' learning success after utilizing this tool. Furthermore, this tool was viewed from the post-test improvement results compared to the pre-test with average values of 80.60 and 41.96, respectively. Some other studies have concluded that using PhET improves students' learning experiences if used simultaneously, as evidenced by the testing cycle (cycle 1 = 84.64 and cycle 2 = 91.86). They respond properly to this tool because it is convenient [10]. The study by [11] proves that PhET simulation-assisted learning is 37% better than the conventional approach, thereby improving the students' science processing skills [11]. The physical Education and Technology (PhET) application is a simulator that displays theoretical results. This phenomenon is true to the original and changes the variables to ascertain their effect on the setup. In accordance with [12]'s opinion, the PhET simulation aspect liked by students is the ability to manipulate and play around with the variables. With these advantages, this tool is an alternative to virtual experimental materials to explore and boost knowledge [13].

PhET aids in building students' science processing skills. It has attractive visual animations and abstract representations that are more explicit [14]. PhET encourages users to be easily understood and master the material studied in class [15]. Educators all over the world tend to use it as a learning medium. Although, it has not been investigated, as proven by several preliminary studies. However, after reviewing it, most related research only emphasized the pedagogical aspect. This includes the effect of PhET on students motivation and achievement, where the visuality (interactivity) aspect was highlighted.

PhET also provides simulations for basic electronic circuits, such as DC analysis [16], familiar measuring tools comprising ammeters and voltmeters, as well as passive components, including resistors and capacitors. Its technical ability to carry out simulations in the case of an electric circuit needs to be researched. PhET competitors, such as MultiSIM, Circuit Wizard, Proteus, etc are capable of being used on complex circuits, meaning that these are technically fulfilled. Students at an advanced level can use it as a learning tool. PhET is a simulator dedicated to beginners or those at elementary, junior, and senior high schools, therefore the aspects of interactivity and availability are emphasized. Students also use it at the higher education level only if they can carry out simulations for basic or simple electrical circuits, commonly studied at universities.

Although no research has discussed this issue, analyzing the exploration and comparison of electronic software is quite an interesting topic. However, [17] compared the MultiSIM, Proteus, and Circuit Wizard simulators as well as their impact on the Wheatstone bridge circuit. Several simulators were compared and tested on a voltage divider circuit [18], [19]. This research discusses offline and online PhET simulators and their use to simulate various basic electronic circuits. These are regarded as the confirmation form of robust performance in the technical aspects. The contributions of this research are summarized as follows:

a) To investigate the PhET performance in terms of simulating basic electronic circuits. These are often studied in electrical engineering or physics departments (e.g., Kirchoff I and II, Voltage divider, series or parallel resistor, Wheatstone bridge, Star – Delta resistor, Mesh) and viewed from a DC analysis (i.e., focuses on voltage and amperage).

b) To compare the theoretical calculations realized from each basic electronic circuit, the simulation results of online and offline PhET are defined in terms of 1) its correctness or suitability, both polarity, and numbers, 2) decimal scale accuracy, 3) the ability to measure instruments to simulate electric current and voltage, and 4) accessibility limitations.
c) The PhET simulators' performance was compared to the various basic electronics previously defined to draw conclusions and provide recommendations from the results obtained.

II. Research Method

This study uses observation method on PhET interactive simulator. This study brings new topics and raises new issues concerning a software (simulator) evaluation for basic electronic circuits that can be attempted as learning media for students in higher education. Furthermore, this research idea can later be applied to assess simulators similar to PhET, such as DCAC LabTM, Circuit LabTM, ThinkerCADTM, Circuit Simulator AppletTM, QUCSTM, SimulIDETM, and many more.

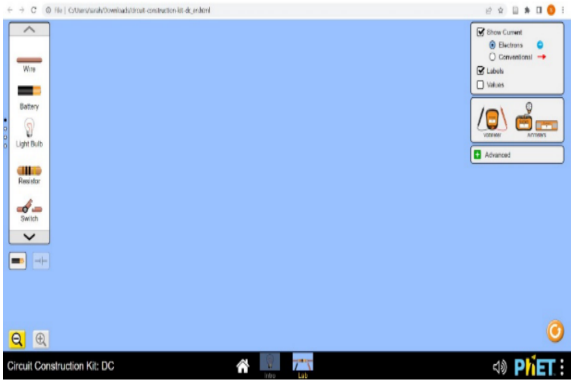


Fig. 1. Online type of PhET preliminary appearance.

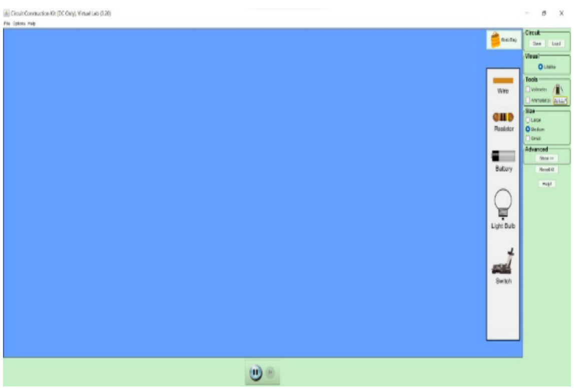


Fig. 2. Offline type of PhET preliminary appearance.

In the present research, online (Fig. 1) and Offline (Fig. 2) PhETs were evaluated by reviewing their availability, technicality, and interactivity. These were realized using several basic electronic circuits commonly studied at universities under related courses. For example, electronics, electrical circuits, physics courses, etc. Table 1 is a profile of the PhETs, namely online (version 1.2.7) and offline (version 3.20), used in the present research. The simulation data was collected from July 15 to November 10, 2022. Therefore, the latest online and offline versions of PhET appear as a disclaimer after the data collection period. Although, the data acquired from it is not shown in the experimental table.

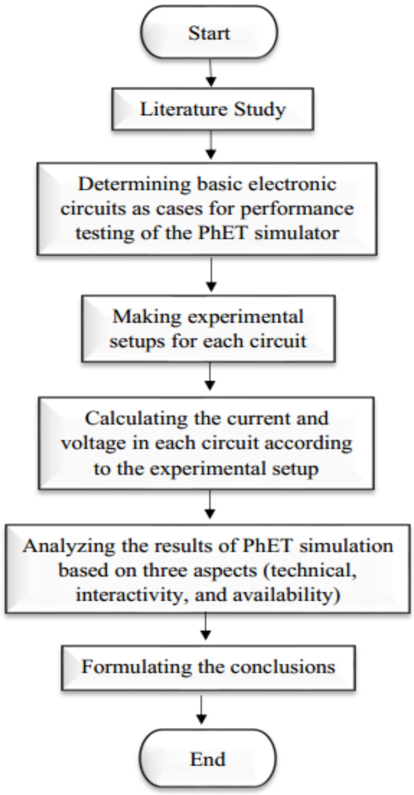


Fig. 3. Flowchart of the study.

Fig. 3 illustrates the research flow starting from a literature study on relevant research; it was summarized that PhET exploration on basic electronic circuits in terms of technicality, availability, and user interactivity has never been done by any researcher in the world. The next step is to compose the electronic circuit to be simulated using PhET. Then, the experimental setup is determined. After-ward, calculations are made using proper formulas. The circuits are then simulated by PhET and compared with the theory (technical aspects), followed by observing the other two aspects. Finally, conclusions can be drawn based on the results of the experiment.

In terms of appearance, online looks more attractive, while in terms of features, offline is complete. Both have complete components, but the online type is separated by the construction, while the offline is in one construction. PhET online has certain advantages in appearance, which is more attractive, while the offline type has more complete instruments. In the online, the designed series cannot be saved, while in the offline type, it is saved in a folder on the computer.

Table 1. PhET Online and Offline

No	Variable	PhET online	PhET offline
1	Access	Free	
2	Simulator version	Circuit construction kit: DC - Virtual Lab 1.2.7	Construction Kit Series (AC + DC) 3.20
3	Component availability	Complete, but separated by construction	Complete in one construction
4	Advantages	More attractive appearance. Easily accessible. There is a screenshot feature.	More complete instruments. The series created can be saved. There is a play and stop button.
5	Disadvantages	The series created cannot be saved. There is no play and stop buttons	Unattractive appearance. There is no screenshot feature. Requires additional software to access it.

Next, after the circuit has been simulated on PhET, some analysis which entails paying attention to the computational results of the mathematical calculation, was performed. The first conclusion answered whether the PhET simulator's performance can resolve the case studies of basic electronic circuits. The research's workflow is shown in Fig. 3. The first step is to carry out a literature review related to the raised topic, namely the PhET evaluation regarding the technical, interactivity, and availability aspects. The results realized show that no research specifically discusses this issue.

The circuit determination, which serves as a test case, was defined, and nine attributes were obtained, namely (1) voltage divider, (2) series, (3) parallel resistors, (4) Wheatstone bridge, (5) Star – Delta resistor, (6) Kirchoff's Law I, (7) Kirchoff II, (8) Mesh with two, and (9) three loops. These nine circuits are shown in Fig. 3, and each of them is then detailed into several Experimental Set-ups with innumerable variables to ensure the reliability of the online and offline PhET simulators, alongside the suitability of the computational and calculated results. The variables include changing the value of the resistor and the input voltage (V_{in}). It also includes examining the voltage and current results on each resistor in the test circuits. The final result is the recommendation that PhET may or may not be an aspect of basic electronics learning in universities.

Apart from the technical aspects, two others namely interactivity and availability were also studied. Based on the literature review, PhET is a tool that offers a good user interface, thereby enabling easy interaction. In this research, the interactivity aspect is reviewed using one of the basic electronic circuits where the voltage is increased to exceed the resistor components' maximum power. Theoretically, the resistor tends to heat up and burn out. Although, through this experiment, certain information is obtained concerning whether or not PhET can simulate burning components. As for the affordability aspect, PhET was examined to determine whether or not it is easy or difficult to access both online and offline versions.

Fig. 4 (a) is a voltage divider circuit in the simulation, which consists of one V_{in} and two resistors arranged in series. It divides V_{in} into several output voltages (V_{out}) required by other components. The V_{in} used in the experiment tends to vary, namely 1.5 V, 3 V, and 9 V. Meanwhile, the values of the resistors also vary, as shown in Table 2. There are three resistor combination setups in the voltage divider circuit. This includes the value of the first resistor (R_1) being greater than the second one (R_2), $R_1 = R_2$, and $R_1 < R_2$. These variables are calculated using the formula in (1).

$$V_{out} = V_{in} \times \frac{R_2}{R_2 + R_1}, if R_1 = R_2 \rightarrow V_{out} = \frac{1}{2} V_{in} \quad (1)$$

Fig. 4 (b) shows that a simple series resistor circuit, consisting of one V_{in} and two parallel resistors, was used in the experiment. The current (I_R) and voltage on each resistor (V_R) were measured. The values of the resistor (as shown in Table 3) and the voltage also varies (1.5 V, 3 V, and 9 V). In respect to the series circuits, there are four set-ups for different resistor combinations, namely R_1 = R_2, R_1 is one-tenth of the value of R_2. Furthermore, the R_1 and R_2 use the market's appropriate and free values. These variables are calculated using (2) and (3) for the total current and voltage across each resistor. In a series circuit, all the resistors have the same current (total current), but the voltages differ.

$$V_R = V_{in} \quad (2)$$

$$V_R = I_R \times R \quad (3)$$

Fig. 4 (c) is a simple parallel resistor circuit consisting of one battery as V_{in} and two resistors. In addition, I_R and V_R in the parallel circuit were measured. The V_{in} value is also similar to the series circuit setup, namely 1.5 V, 3 V, and 9 V (Table 4). The setup for the parallel resistor test circuit is the same as the series, R_1 = R_2, then R_1 is one-tenth of the value of R_2. Moreover, R_1 and R_2 use the appropriate and accessible values in the market. These variables are calculated using (4), where the value of each resistor (V_R) is equal to the V_{in}. For example, V_{in} is 5 V supplies three resistors (R_1, R_2, and R_3) connected in parallel. Then voltage of R_1, R_2, and R_3 (then denoted as V_{R1}, V_{R2}, and V_{R3}) is equal to 5 V, precisely same with V_{in}. Eq. (5) shows the current flowing in each resistor (I_R) is the division between the resistor (R) and V_{in} or the voltage across the resistor (V_R); this equation is written based on Ohm's Law where $I = V/R$.

$$V_R = I_R \times R \quad (4)$$

$$I_R = \frac{V_R}{R} \quad (5)$$

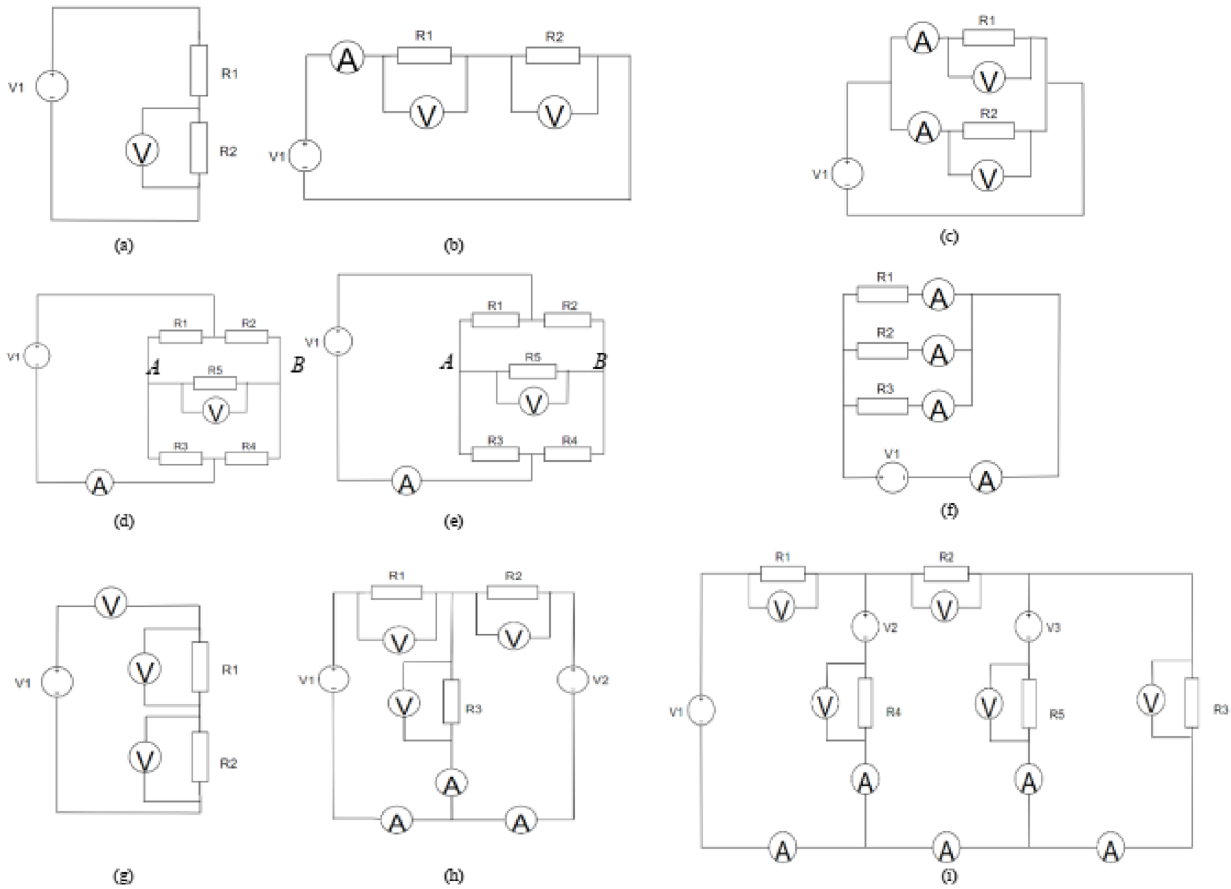


Fig. 4. Experimental circuit: (a) Voltage divider; (b) series; (c) Parallel; (d) Wheatstone bridge; (e) Star-–delta resistors; (f) Kirchoff's law I; (g) Kirchoff II; (h) Mesh with two loops, and (i) Mesh with three loops.

Table 2. Voltage Divider

Setup	$V_{in}(V)$	$R_1(\Omega)$	$R_2(\Omega)$	$V_{out}(V)$ **Theory**	V_{out} **(V) Simulation**	
					PhET Offline	**PhET Online**
$R_1 > R_2$	1.5 V	15 Ω	8 Ω	0.52 V		
	3 V	24 Ω	12 Ω	1.00 V		
	9 V	32 Ω	10 Ω	2.14 V		
$R_1 = R_2$	1.5 V	24 Ω	24 Ω	0.75 V		
	3 V	18 Ω	18 Ω	1.50 V		
	9 V	6 Ω	6 Ω	4.5 V	4.49 V	4.50 V
$R_1 < R_2$	1.5 V	4 Ω	12 Ω	1.125 V		1.13 V
	3 V	28 Ω	72 Ω	2.16 V		
	9 V	20 Ω	25 Ω	5.00 V		

Fig. 4 (d) is a Wheatstone bridge circuit consisting of four resistors (R_1, R_2, R_3, and R_4) arranged like a bridge and then connected to V_{in} and one resistor (R_5) connected between points A and B. Experiments were carried out using this circuit test to determine whether or not PhET is used to prove a state of balance. The essence is to determine whether or not the value of R in a material can be known by changing its other variables to get a balanced state. In other words, the voltage value at R_5 = 0 V (the voltage at points A and B are equal to 0 V, or V_{AB} = 0), and no current flows in R_5 (I_{R5} = 0 A) [12]. The R_5 existence can be neglected and is directly solved by the Wheatstone bridge circuit equation, namely $R_1 \times R_4 = R_2 \times R_3$.

There are two setups in the experiment, as shown in Table 5. The first setup involves the selection of four resistors that are similar to each other ($R_1 = R_2 = R_3 = R_4$), thereby ensuring it is balanced. The second setup is that the four resistors have different values ($R_1 \neq R_2 \neq R_3 \neq R_4$) but are still balanced. The voltage at points A and B can be determined using (6) and (7), respectively, and it refers to circuit on Fig. 4 (d). Furthermore, the state of balance is expressed in (8), where the difference between the voltage at points A and B equals 0 V; simply it can be expressed as V_{AB} = 0.

$$V_A = \frac{R_3}{R_1 + R_3} \times V_{in} \tag{6}$$

where V_A is output voltage between R_1 and R_3 of Fig. 4 (d), and V_{in} is voltage used in the circuit.

$$V_B = \frac{R_4}{R_2 + R_4} \times V_{in} \tag{7}$$

Table 3. Comparison of Theoretical Calculations on Series Circuits toward Online & Offline PhET Simulators

Setup	V_{in}	R_1	R_2	V_{R1}	V_{R2}	I_{R1}	I_{R2}	**PhET Simulation**							
								PhET Online				**PhET Offline**			
								V_{R1}	V_{R2}	I_{R1}	I_{R2}	V_{R1}	V_{R2}	I_{R1}	I_{R2}
R_1=R_2	1.5V	36Ω	36Ω	0.72V		0.04A		0.75V		0.02A		0.75V		0.02A	
	3V	27Ω	27Ω	1.62V		0.11A		1.50V		0.11A		1.5V		0.11A	
	9V	12Ω	12Ω	4.44V		0.75A		4.50V		0.75A		4.5V		0.75A	
$R_1 = \frac{1}{10}R_2$	1.5V	2Ω	20Ω	0.14V	1.4V	0.075A	0.75A	0.14V	1.36V	0.07A	0.75A	0.136V	1.364V	0.075A	0.75A
	3V	4.2Ω	42Ω	0.2V	2.52V	0.071A	0.71A	0.28V	2.72V	0.07A	0.71A	0.273V	2.727V	0.07A	0.71A
	9V	5.6Ω	56Ω	0.84V	8.18V	1.60A	0.16A	0.82V	8.18V	1.61A	0.16A	0.818V	8.182V	0.16A	1.61A
Existing resistors in the market	1.5V	12Ω	22Ω	0.48V	0.88V	0.068A	0.125A	0.55V	0.95V	0.07A	0.13A	0.529V	0.971V	0.07A	0.12A
	3V	43Ω	24Ω	1.72V	0.96V	0.125A	0.069A	1.9V	1.07V	0.12A	0.07A	1.925V	1.075V	0.12A	0.07A
	9V	15Ω	56Ω	1.95V	7.28V	0.16A	0.6A	1.90V	7.10V	0.16A	0.60A	1.901V	7.098V	0.16A	0.60A
Free Resistors	1.5V	17Ω	23Ω	0.68V	0.92V	0.065A	0.088A	0.64V	0.86V	0.07A	0.09A	0.637V	0.862V	0.07A	0.09A
	3V	28Ω	37Ω	1.4V	1.85V	0.081A	0.107A	1.29V	1.71V	0.08A	0.11A	1.292V	1.708V	0.08A	0.11A
	9V	40Ω	52Ω	4V	5.2V	0.173A	0.225A	3.91V	5.09V	0.17A	0.23A	3.913V	5.087V	0.17A	0.22A

Table 4. The Results of Parallel Circuit Calculations Using a Parallel Simulator

Setup	V_{in}	R_1	R_2	**Theory Calculations**				**PhET Simulation**						
								Online			**Offline**			
				V_{R1}	V_{R2}	I_{R1}	I_{R2}	V_{R1} &V_{R2}	I_{R2}	I_{R1}	V_{R1}	V_{R2}	I_{R1}	I_{R2}
R_1=R_2	1.5V	36Ω		1.5V		0.04A		1.5V	0.04A		1.5V		0.04A	
	3V	27Ω		3V		0.11A		3V	0.11A		2.999V		0.11A	
	9 V	12Ω		9V		0.75A		9 V	0.75A		8.996V		0.75A	
$R_1 = \frac{1}{10}R_2$	1.5V	2Ω	20Ω	1.5V		0.75A	0.075A	1.5V	0.75A	0.07A	1.498V		0.75A	0.07A
	3V	4.2Ω	42Ω	3V		0.71A	0.071A	3V	0.71A	0.07A	2.998V		0.71A	0.07A
	9 V	5.6Ω	56Ω	9V		1.60A	0.160A	9V	1.61A	0.16A	8.995V	8.996V	1.61A	0.16A
Existing resistors in the market	1.5V	12Ω	22Ω	1.5V		0.125A	0.068A	1.5V	0.12A	0.07A	1.499V	1.5V	0.12A	0.07A
	3V	43Ω	24Ω	3V		0.069A	0.125A	3V	0.07A	0.12A	2.999V		0.07A	0.12A
	9V	15Ω	56Ω	9V		0.6A	0.160A	9V	0.60A	0.16A	8.998V		0.60A	0.16A
Free Resistor	1.5V	17Ω	23Ω	1.5V		0.088A	0.065A	1.5V	0.09A	0.17A	1.5V		0.09A	0.07A
	3V	28Ω	37Ω	3V		0.107A	0.081A	3V	0.11A	0.08A	2.999V		0.18A	0.13A
	9V	40Ω	52Ω	9V		0.225A	0.173A	9V	0.22A	0.17A	8.999V		0.22A	0.17A

where V_B is output voltage between R_4 and R_2 of Fig. 4 (d), and V_{in} is voltage used in the circuit.

$$V_{AB} = V_A - V_B = 0V \tag{8}$$

where V_{AB} is a voltage measured on R_5.

The next test circuit is the Star—Delta resistor on Fig. 4 (e). It uses the same construction as the Wheatstone bridge, but the voltage from point A to point B is not equal to 0 V ($V_{AB} \neq 0$). In other words, there is a current flowing through R_5, therefore its existence need not be ignored. The delta circuit is changed first to a star type [20]. The three equivalent resistors were determined, and their total was calculated. In this circuit, search for the star—delta resistor's total current with reference to (9). The resistor values are varied with V_{in} = 1.5 V, 3 V, and 9 V, as shown in Table 6. All resistors employed standard values.

$$I_{tot} = \frac{V}{\frac{(R1+R3)\times(R_2+R_4)}{R_1+R_2+R_3+R_4}} \tag{9}$$

Fig. 4 (f) is a circuit that adheres to Kirchhoff's Current Law (KCL). The circuit is composed of one V_{in} and three resistors arranged in parallel. Virtual ammeters are installed on each incoming line on the three resistors (I_1, I_2, and I_1). An ammeter is installed before the intersection to measure the total current (I_{tot}). The experiment used V_{in} = 18 V and a resistor valued at 24 Ω and 48 Ω. The measured current values at I_1, I_2, and I_3 are 2 A, 1.5 A, and 2.5 A (Table 7), respectively. Kirchoff, I state that the sum of the incoming and outgoing electric currents at a point is 0 A. Therefore, incoming current (I_{in} as I_{tot}) equals I_{out}, the sum of I_1, I_2, and I_3. Calculations, in theory, refer to (10).

$$I_{in} = I_1 + I_2 + I_3 = I_{out} \tag{10}$$

$$\sum \varepsilon = \sum IR = 0 \tag{11}$$

Fig. 4 (g) is a circuit that adheres to Kirchoff's Voltage Law (KVL). The circuit is arranged with one V_{in} and resistor in series. Three virtual voltage meters are further installed at the ends of R_1 and R_2 as V_{tot} or total voltage (V_3), then V_1 and V_2 are installed on R_1, and R_2, respectively. This experiment used V_{in} = 18 V and three resistor value setups. The first setup is 24 Ω and 48 Ω for R_1 and R_2, respectively, while the second one is 15 Ω and 15 Ω, and the third is also 30 Ω and 25 Ω. Kirchoff II states that the sum of the voltages in a closed circuit is 0 V ((11)), where ε is the source voltage and $I \times R$ is the voltage across each resistor. Therefore, the voltage in R_1 and R_1 is the same as in V_{in}.

Fig. 4 (h) is a 2-loop mesh circuit to evaluate whether or not PhET is used to calculate current and voltage in a branched or closed circuit. In addition, it is composed of two V_{in} and three resistors. An ammeter is installed at each branch to measure the current R_1, R_2, and R_3.

The values of the two V_{in} resistors vary in the three setups, are shown in Table 9 and Table 10.

Fig. 4 (i) is a 3-loop mesh circuit slightly more complex than the 2-loop. This experiment aims to ascertain whether or not PhET is used to calculate current and voltage in closed DC circuits, which are a bit complex with many branches. This type is composed of three V_{in} and five resistors. An ammeter is installed at each branch to measure the current in R_1, R_2, and R_3. In this experiment, only one setup was used, namely the V_{in} value was fixed, where V_1 = 9 V, V_2 = 6 V, and V_3 = 3 V. Sementara, untuk resistor dipilih fixed, such as R_1 = 3 Ω, R_2 = 4 Ω, R_3 = 5 Ω, R_4= 6 Ω, and R_5 = 7 Ω.

III. Result

This section discusses the technical aspect, interactivity aspect, and availability aspect.

A. Technical Aspect

In this aspect, the theoretical calculations for several basic electronic circuits were compared with the online and offline PhET simulations. The first circuit used as a PhET test case is a voltage divider circuit shown in Fig. 4 (a). The test results are shown in Table 2, and for this circuit, three setups were made. In the first setup, R_1 ¿ R_2, eg R_1 = 15 Ω and R_2 = 8 Ω, with V_{in} = 1.5 V.

The results obtained were calculated using (1), where V_{in} is multiplied by the R_2 and divided by the value of the two resistors in the circuit (R_1 and R_2). The result obtained is 0.52V, where V_{out} in the first setup is less than V_{out} when R_1 ¡ R_2 (third setup). Next, the second setup is R_1 = R_2, where V_{out} is always half the value of V_{in}. The second setup also confirms (1), where the two resistors are the same value, then V_{out} is automatically half the value of V_{in}. The results of the PheT computations show that the values correspond to the theoretical calculations. In the cases of R_1 = 4 Ω and R_2 = 12 Ω, with V_{in} = 1.5 V, there is a difference between online and offline simulations. This difference is insignificant because it only differs in rounding the number after the decimal point. Likewise, the data obtained at the settings R_1 = 6 Ω and R_2= 6 Ω, with V_{in} = 9 V, the V_{out} value in the offline PhET simulation has a difference of 0.01 from the theoretical calculations and online simulations.

In the series circuit simulation, there are four setups. In the first one, R_1= R_2 is determined, for example, the two resistors have a value of 36 Ω while V_{in} = 1.5 V. The simulation results confirmed the calculated results, when R_1 = R_2, the voltage on each resistor tends to be equivalent (V_{R1} = V_{R2}), while that for each resistor is half of V_{in}. Moreover, I_{R1} is equal to I_{R2}, which is the current distributed by I_{tot}. In the second setup, R_1 = $\frac{1}{10}R_2$, the numbers for the two convenient resistors were selected, for example, R_1 = 2 Ω, R_2 = 20 Ω. With V_{in} = 1.5 V, the simulation results show that the voltage and current on R_1 (0.136 V and 0.075 A) are approximately $\frac{1}{10}$ of these variables in R_2 (1.36 V and 0.75 A), which confirms the theoretical calculations.

Interestingly, PheT is capable of computing comma numbers. In the third setup, the values of the resistor are used in the market. For example, R_1 = 12 Ω, R_2 is 22 Ω with V_{in} = 1.5 V. Regarding the resistors in the market, the online PhET computed results of V_{R1} and V_{R2} are slightly different from the theoretical calculations (difference of 7). This only occurs with certain combinations of resistors, and it was concluded that PhET carries out simulations using mathematical calculations, shown in (2) and (3) with commercial resistors. In the fourth setup, a resistor is selected with a random value unavailable in the market, such as R_1 = 17 Ω, R_2 = 23 Ω was used. The PhET simulation results have similar values as the calculations, where the current flowing through each resistor is the same, and the voltage is different, except when R_1 = R_2. This shows that it is an input of random resistor values. Red is used in the text for voltage variables and green for current to make it easier to compare the three data.

Suppose there are the same numbers among the three data in Table 3 and Table 4 (offline/online PhET simulations and calculations). In that case, the texts are colored green for the current value, while the red color shows the same value as the voltage value. With this color difference in the texts, readers are expected to compare the resulting data from many data sets. When examined carefully, offline PhET has an average deviation of approximately 0.01, alongside the online version and mathematical calculations.

The parallel circuit simulation results realized from the four setups are shown in Table 4. The setup used and its components are the same as the series resistor circuit, namely (1) R_1= R_2, (2) $R_1 = \frac{1}{10}R_2$, (3) resistors that match commercially available values, and (4) those that are random or unavailable in the market. The results show that online and offline PhET simulations are computed according to theoretical calculations realized using (4) and (5). The voltage across each resistor is the same, while the current flowing through them differs except for the condition R_1= R_2.

Table 5 compares the online and offline PhET simulation results of (8) on the Wheatstone bridge circuit. Interestingly, two set-ups are used to prove their equilibrium state. In theoretical calculations, the two set-ups produce $V_{AB} = 0$, while the first is R_1= R_2=R_3= R_4, and the second is $R_1 \neq R_2 \neq R_3 \neq R_4$. Considering the first set-up, the values for R_1, with R_2, R_3, and R_4, are the same with the selection of 30 Ω. In the second set-up, different resistor values were chosen. For example, in the test table, R_1 = 16 Ω, R_2 = 22 Ω, R_3 = 23 Ω, and R_4 = 33 Ω. Referring to the first and second setup, the voltage across the fifth resistor in the

Table 5. The Test Results of The Wheatstone Bridge Circuit on PhET and its Comparison to The Calculated Results

Setup	V_{in}	R_1	R_2	R_3	R_4	V_{R5}			I_{total}		
						Theory	**Online**	**Offline**	**Theory**	**Online**	**Offline**
R_1=R_2=R_3=R_4 (Balance)	1.5 V	30 Ω				0 V			0.05 A		
	3 V	30 Ω				0 V			0.1 A		
	9 V	30 Ω				0 V			0.3 A		
$R_1 \neq R_2 \neq R_3 \neq R_4$ (Balance)	1.5 V	16 Ω	22 Ω	24 Ω	33 Ω	0 V			0.06 A		
	3 V	16 Ω	22 Ω	24 Ω	33 Ω	0 V			0.12 A	0.13 A	
	9 V	16 Ω	22 Ω	24 Ω	33 Ω	0 V			0.38 A	0.39 A	

circuit (V_{R5}) is 0 V or no current flows through R_5. PhET has confirmed (8), where the Wheatstone bridge circuit principle is in equilibrium $V_{AB} = 0$. Meanwhile, there are insignificant differences, with an average of 0.01 for the I_{tot} parameters that flow in the circuit for several resistor cases.

Table 6 shows the data for testing the Star – Delta resistor circuit, which is constructively similar to the Wheatstone bridge circuit. The difference is that a random resistor value is chosen, therefore, the circuit is not balanced ($V_{AB} \neq 0$, or there is a current flowing in R_5). Based on this reason, the I_{tot} search is realized through the Delta (Δ) to Star (Y) conversion mechanism, and then the equivalent resistor is calculated. I_{tot} was calculated using (9) moreover, the V_{in} variation was also adjusted to the other circuits in the experiment, namely 1.5 V, 3 V, and 9 V. There is a difference of 0.01 between the calculated results and offline and online PhET simulations for several cases. It simply means that the PhET accuracy is 99.99%. With respect to the research limitation, the value of the current flowing in R_5 was not calculated and compared to the simulation in the Star–Delta resistor circuit experiment.

Table 7 shows the experimental results of a simple parallel circuit as KCL proof. The total incoming current is equal to the outgoing current assumed during the experiment. The values I_1, I_2, and I_3 are 2 A, 1.5 A, and 2.5 A, respectively, with an I_{tot} of 6 A. The results of PhET calculations and simulations show an equivalence of 6.00 A. However, under the conditions I_1=I_2=I_3=3 A, the calculation and simulation results are 9.00 A. There is a difference of 0.01 A for certain cases. Table 8 shows the experimental results on a simple series circuit as proof of KVL. Referring to the theory ((11), the total voltage in a closed circuit is 0 V. In the experiment, V_1 and V_2 are 6 V and 12 V, with V_{tot} of 18 V, according to the V_{in} value. The results of PhET calculations and simulations have the same value of 18 V. The data obtained has a difference of 0.01 A in certain cases. For example, on V_1, theoretical calculations resulted in 9.9 V. Meanwhile, offline and online PhET are 9.818 V and 9.82 V, when added to the V_2, the result is 9.9 V.

The two-loop Mesh circuit simulation results are shown in Table 9 and Table 1010 for the current and voltage parameters, respectively. Its analysis in this setup involves using KVL ((11)). The experimental circuit has a resistor between the two loops (R_2). The current in each resistor is detected by making a loop first, and after obtaining the equation for each, it is solved by either substitution or Matrix Crammer. If the current in the loop is negative, it indicates a difference between the direction of the conventional current and itself. The voltage of each resistor is realized by multiplying its value with the current flowing through the resistor. The simulation results show that the current value at the branch has been confirmed according to theory with various setups (setup I: V_1<<V_2, setup II: V_1<V_2, setup III: V_1>V_2), however, there are insignificant differences of relatively 0.02 A to 0.03 A.

Moreover, the three-loop Mesh circuit simulation results are shown in Table 11 and Table 12 for the current and voltage measurements, respectively. The five current measurement points (I_1, I_2, I_3, I_4, and I_5) and voltage (V_1, V_2, V_3, V_4, and V_5) in the circuit were investigated. The results show that with a multi-branch circuit, PhET can carry out simulations with a difference of approximately 0.02 A to 0.03 A and relatively 0.1 V to 0.2 V for current and voltage measurements, respectively. In the three-loop Mesh analysis, only one setup was used where the source voltage (V_1 = 9 V, V_2 = 6 V, V_3 = 3 V) and resistor (R_1 = 3 Ω, R_2 = 4 Ω, R_3 = 5 Ω, R_4 = 6 Ω, and R_5 = 7 Ω) is fixed.

B. Interactivity Aspect

Through these experiments, it has been confirmed that PhET has good interactivity. It provides components and measuring instruments that are true to the original, such as a virtual online and offline laboratory display, as shown in Fig. 5 a–d and Fig. 5 e–f. Examples include cable items, batteries, lights, resistors, capacitors, coils (inductors), switches, voltmeters, etc. The options displayed when the circuit is run electron charge symbol and arrows indicating conventional, as shown in Fig. 5 g. In the Conventional view, the circuit shows the current direction when running. Meanwhile, the electron display illustrates the movement of electrons in the opposite direction to the current, following the theory. Users can check the label to display the resistors' component names.

When this component is unchecked, only an image will be displayed with a tick value, which shows the resistor number. Fig. 5(g) display is a typical example of online PhETs. On the offline tool, only the electron animation is displayed. Fig. 5(h) is a simple closed-loop circuit consisting of a battery, resistor, and a load in

Table 6. Test Results for The Star-–Delta Resistor Circuit on PhET and its Comparison to The Calculated Results

V_{in}	R_1	R_2	R_3	R_4	V_{R5}	I_{total} **(Theory)**	I_{total} **(Simulation)** PhET Offline	PhET Online
1.5 V	20 Ω	40 Ω	30 Ω	60 Ω	10 Ω	0.04 A		0.05 A
	24 Ω	36 Ω	22 Ω	33 Ω	17 Ω	0.06 A	0.05 A	
	30 Ω	10 Ω	60 Ω	20 Ω	50 Ω	0.07 A		
3 V	20 Ω	40 Ω	30 Ω	60 Ω	10 Ω	0.09 A		
	24 Ω	36 Ω	22 Ω	33 Ω	17 Ω	0.10A	0.11A	
	30 Ω	10 Ω	60 Ω	20 Ω	50 Ω	0.13 A		
9 V	18 Ω	93 Ω	12 Ω	62 Ω	35 Ω	0.35 A	0.13 A	
	80 Ω	40 Ω	20 Ω	10 Ω	60 Ω	0.27 A		
	12 Ω	42 Ω	16 Ω	56 Ω	22 Ω	0.41 A		

Table 7. The Results of The Trial Series of Kirchoff's Law I Proof on PhET and its Comparison to The Calculated Results

I_1	I_2	I_3	I_{out} or I_{tot} **Theory**	**PhET Offline**	**PhET Online**
2 A	1.5A	2.5 A	6.00 A		
2 A	2 A	4 A	8 A	7.99 A	8.00 A
3 A	3 A	3 A	9.00 A		

the lamp form on the online mode electron-type PhET media. Meanwhile, the conventional mode is shown in Fig. 5 (i). The moving animation describing the direct and reverse direction of the conventional current and electrons in PhET can be seen by the theory. Fig. 6 and Fig. 7 display the experimental series for all online and offline cases in the environments, respectively. From Fig. 6 and Fig. 7, it can be summarized that PhET serves an excellent user interface and is friendly to the students. The user can drag and drop components quickly and then connect them to instrumental measurements like an actual experiment by available probes.

In PhET, the Volt meter and Ampere meter can display the results based on mathematical calculations of each circuit. Furthermore, conventional current or electron flows within the circuits can be visualized clearly. The data in Table 2 until Table 12 are obtained by looking at the voltage and voltage displayed by the virtual voltmeter and Ammeter. The differences in appearance due to the two limitations of the voltmeter measuring instrument on the online tool do not affect the PhET interactivity. Therefore, for some proofs, the voltage across some resistors or the total voltage magnitude cannot be shown. The users can choose to use the online tool when connected to a network or offline when the circuit is made later and stored on a computer.

Furthermore, animations in PhET help students understand the behavior of voltages and currents in real conditions. When the circuit runs in the simulation, electrons move from the negative (–) to the positive (+) pole. Meanwhile, if the conventional current is checked, the animation will display the current direction from positive (+) to negative (–). For example, when the voltage applied to a resistor exceeds the maximum current rating, the resistor will burn out. At the same time, when the small resistor value is entered into a very high battery voltage, they both explode.

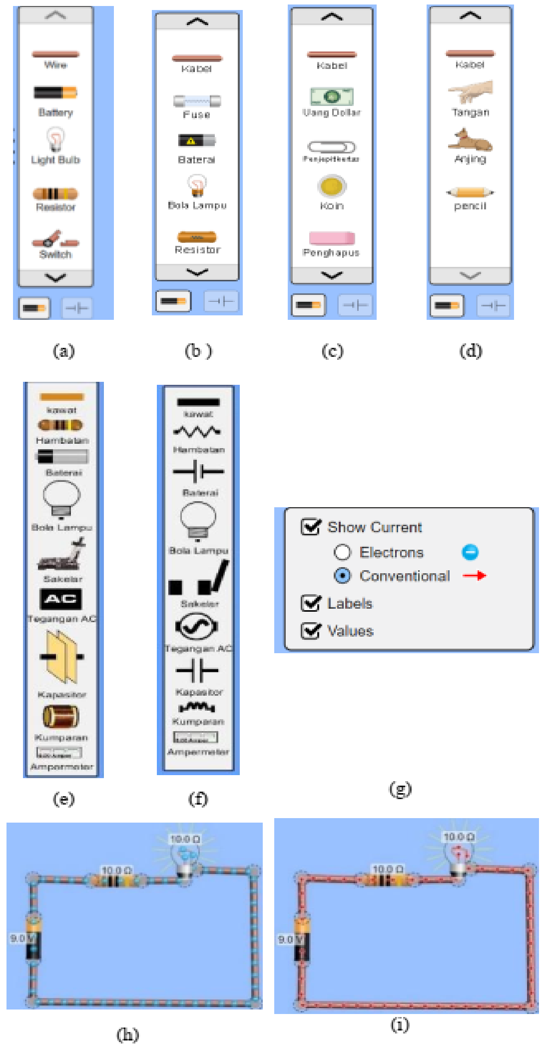


Fig. 5. The display of the PhET simulator: (a–d) Components available in PhET online; (e–f) Components available on offline PhET; (g) Simulated displays; (h) Circuit with electron mode display; (i) a Circuit with a conventional mode display.

Fig. 8 (a) is a screen-shot from PhET Online, which displays a voltage divider circuit of both resistors burning at once V_{in}, with the values set to very small (by 1 Ω) and above 30 V. This means that the current limit through the resistor is above its maximum power rating. The resistor used has a power of $\frac{1}{4}$ Watt, while the current flowing is ∼30 A. Fig. 8 (b) is the resistor condition in the Wheatstone bridge circuit with four burnt resistors (R = 1 Ω and V_{in} = 30 V). However, only one resistor is not burnt because the circuit is balanced,

Table 8. The Results of The Trial Series of Kirchoff's Law II Proofs on PhET and The Comparison to The Calculated Results

V_{in}	R_1	R_2	V_{tot}			V_{R1}			V_{R2}		
			Theory	**Offline**	**Online**	**Theory**	**Offline**	**Online**	**Theory**	**Offline**	**Online**
18 V	24 Ω	48 Ω	18 V			6 V			12 V		
	15 Ω	15 Ω	18 V			9 V			9 V		
	30 Ω	25 Ω	18 V			9.9 V	9.818 V	9.82 V	8.25 V	8.128 V	8.18 V

Table 9. Test Results of The Two-loop Mesh Circuit on PhET and The Comparison to The Calculated Results (for Variable Electric Current)

Setup	V_1	V_2	R_1	R_2	R_3	I_1			I_2			I_3		
						Theory	**Offline**	**Online**	**Theory**	**Offline**	**Online**	**Theory**	**Offline**	**Online**
1	6 V	9 V	5 Ω	9 Ω	14 Ω	0.24A			0.54A			0.3A		
2	9 V	12 V	10 Ω	12 Ω	15 Ω	0.22A			0.57A			0.35A		
3	12 V	10 V	8 Ω	6 Ω	14 Ω	0.72A		0.74A	1.03A	1.04A	1.02A	0.31A		0.28A

Table 10. Test Results of The Two-loop Mesh Circuit on PhET and The Comparison to The Calculated Results (for Voltage Variables)

Setup	V_1	V_2	R_1	R_2	R_3	V_{R1}			V_{R2}			V_{R3}		
						Theory	**Offline**	**Online**	**Theory**	**Offline**	**Online**	**Theory**	**Offline**	**Online**
1	6 V	9 V	5 Ω	9 Ω	1 Ω	1.2V	1.182V	1.18V	4.86V	4.817V	4.82V	4.2V	4.182V	4.18V
2	9 V	12 V	10 Ω	12 Ω	1 Ω	2.2V			6.84V	6.8V		5.25V	5.2V	
3	12 V	10 V	8 Ω	6 Ω	1 Ω	5.76V	5.777V	5.90V	6.18V	6.222V	6.10V	3.1V	3.77V	3.90V

Table 11. Comparison between The Three-loop Mesh Circuit Currents in Theoretical Calculations against the PheT Simulator with V_1 = 9 V, V_2 = 6 V, V_3 = 3 V, R_1 = 3 Ω, R_2 = 4 Ω, R_3 = 5 Ω, R_4 = 6 Ω, and R_5 = 7 Ω

I_1	I_2	I_3		I_4	I_5	
Theory, Offline, Online	**Theory, Offline, Online**	**Theory**	**Offline & Online**	**Theory, Offline, Online**	**Theory**	**Offline & Online**
2.06 A	0.59 A	0.1 A	0.09 A	1.47 A	0.49 A	0.5 A

Table 12. Comparison between The Voltages of The Three-loop Mesh circuit in Theoretical Calculations against The PheT Simulator with V_1 = 9 V, V_2 = 6 V, V_3 = 3 V, R_1 = 3 Ω, R_2 = 4 Ω, R_3 = 5 Ω, R_4 = 6 Ω, and R_5 = 7 Ω

Theory	**Online**	**Offline**	**Theory**	**Online**	**Offline**	**Theory**	**Offline**	**Online**	**Theory**	**Offline**	**Online**	**Theory**	**Offline**	**Online**
6.18V		6.177V	2.36V		2.355V	0.5V	0.467V	0.47V	8.88V	8.821V	8.82V	3.43V	3.467V	3.4V

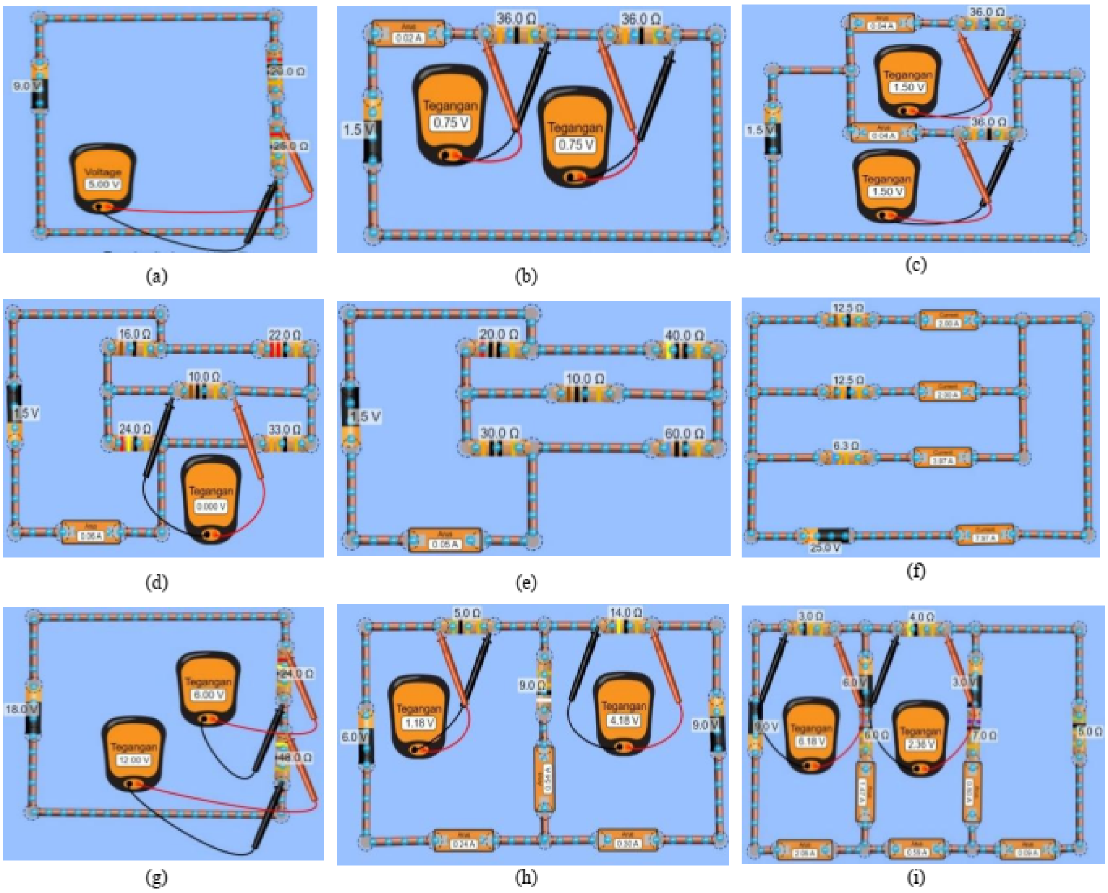
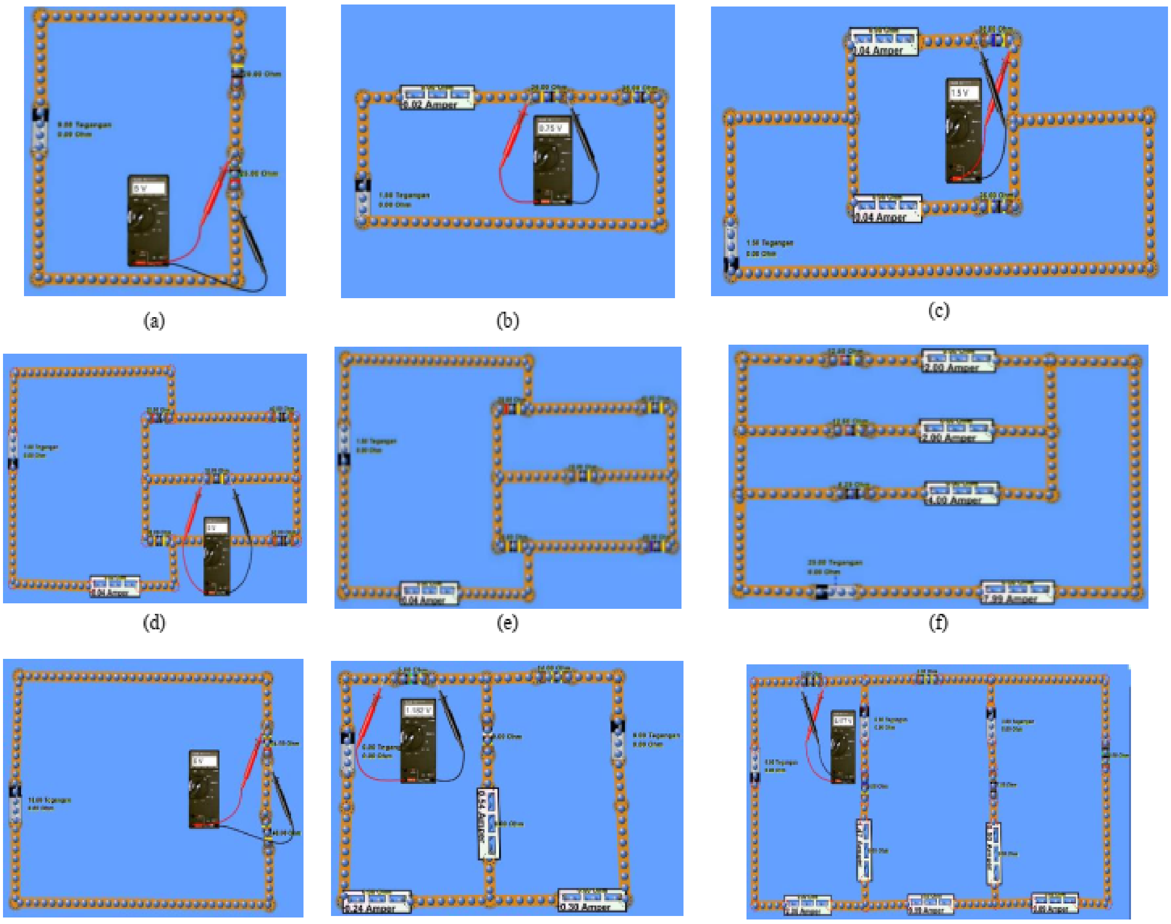
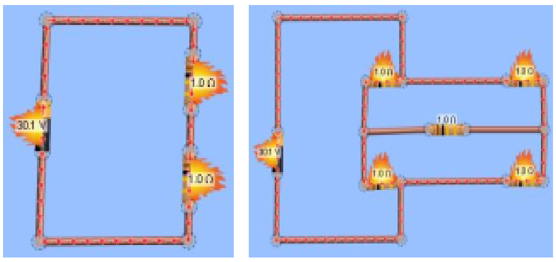


Fig. 6. The results of the PhET online simulator for the circuit: (a) Voltage divider; (b) Series resistors; (c) parallel resistors; (d) Wheatstone bridge; (e) Star—delta resistor; (f) Kirchoff I; (g) Kirchoff II; (h) Mesh with two loops; (i) Mesh with three loops.



(a) (b) (c) (d) (e) (f) (g) (h) (i)

Fig. 7. The results of proving the offline PhET simulator for the following circuits: (a) Voltage divider; (b) Series resistors; (c) Parallel resistors; (d) Wheatstone bridge; (e) Star—delta resistor; (f) Kirchoff I; (g) Kirchoff II; (h) Mesh with two loops; (i) Mesh with three loops.



(a) (b)

Fig. 8. Offline PhET simulator display: (a) Voltage divider circuit; (b) Wheatstone bridge circuit.

with the voltage across R_5, 0 V. This is slightly different from the real situation, where only the resistor should burn. PhET, with this interactive animation, can help students to be careful in determining resistance and voltage values. Therefore, it does not damage the components in the real environment.

C. *Availability Aspect*

PhET is a learning tool for simulating physical phenomena [21], including simple electrical circuits (dynamic electricity) [22], and static electricity [23]. Its advantage is that it provides easy access and offers good interactivity. Hence, it makes it easier for the user to understand a phenomenon, available component features, and complete measuring instruments. On the other hand, searching for items such as components and measuring instruments is easy with communicative symbols.

To access the Offline version of this tool, users need to first download the Java programming language before installing PhET. Meanwhile, the online version is easier to access because it only requires an internet connection and opening the official website of the PhET simulator (https://phet.colorado.edu/). Both can be accessed easily and are free of charge, as shown in Table 1. PhET has fulfilled the availability aspect due to the ease of access for the two types of tools offered. The online simulator (Circuit Construction Kit: DC - Virtual Lab 1.2.7) with the HTML files extension can only be accessed using the internet network. During usage, the user must download the HTML file extension and the Java programming language sequentially.

IV. Discussion

The online and offline PhET simulation results are in accordance with the theoretical calculations for all the basic electronic circuits used in this research, namely (1) voltage divider, (2) series resistor, (3) parallel resistor, (4) Wheatstone bridge, (5) Star – Delta resistor, (6) Kirchoff I, (7) Kirchoff II, (8) Mesh with two loops, and (9) Mesh with three loops. The results were confirmed with several setups in each series. From a technical aspect, PhET meets the criteria to be used by students majoring at the basic level in electrical engineering who wish to research the DC electric circuits characteristics. This tool can be used by students in high school and higher education as a learning device.

Furthermore, the PhET is easily accessible by visiting the provider's page. Users can directly operate the online version or download and install it for offline usage. Interestingly, PhET is free and open to anyone. These results confirm [14]'s opinion that PhET is an alternative for users to simulate an electric circuit without time and limitations. It displays excellent interactivity and a very simple display in the closed electronic circuits behavior, which enables the movement of conventional currents & electrons on PhET online. Item images represent the interactive display of components and measuring instruments according to the original. This allows users to find the items they need easily. The Ammeter needs to be connected to the resistor first before the current flowing in the resistor can be checked. Although this condition is in accordance with the real environment, some other simulators do not need an ammeter. The current value is displayed immediately when the cursor is brought closer to the cable.

In the offline PhET simulator, a screen-shot feature is also found to capture circuit results without using the Screen-shot facility that comes with the laptop. The disadvantage of using the PhET is its ability to limit the number of voltmeters and ammeters in the simulation to two and six in the online type. Therefore, when three voltmeters are needed, it should take turns, else it will not be able to get voltage measurement data in one run or determine the electric current. This is because only two voltage points are measured, followed by the automatic storage of the screen-shot results. Whereas the offline PhET can only use one voltmeter. There can be more than 20 units for ammeters, but when the ammeters are floating or have not been connected to the circuit, 1 unit is used.

The PhET simulator uses the Java programming language with an HTML file extension. Its offline tool can be used after downloading the Java programming language, where the circuit files that have been created can be stored. However, the online simulation can be conducted where the circuit made cannot be saved after downloading the HTML file extension.

In the online version of the PhET simulator, no feature is used to run the simulator, hence the circuit that has been created automatically runs immediately. Therefore, disconnecting one of the cables is necessary to stop the circuit. This is important because it helps to save the series of files that have been performed. When closing the PhET website page, the user has to regenerate the series. Additionally, in the online and offline versions of PhET, the voltage or resistance value should be set using the existing parameters in the range 0 Ω−−120 Ω and 0 V−−120 V, as shown in Fig. 9 (a) and Fig. 9 (b) for online and offline PhET types, respectively. The users cannot input more values than the above range. In both offline and online, changing the resistance value and battery voltage is carried out by sliding the slide. However, the online tool does not provide a manual input feature, unlike the offline one. The PhET Online version provides special batteries and resistors that can be used to simulate high power (>120 V). The display is shown in Fig. 9 (c), where the resistor and voltage can be adjusted to a maximum of 120,000,000 Ω and 100 kV. Meanwhile, offline PhET only provides low-voltage components, as shown in Fig. 9 (d).

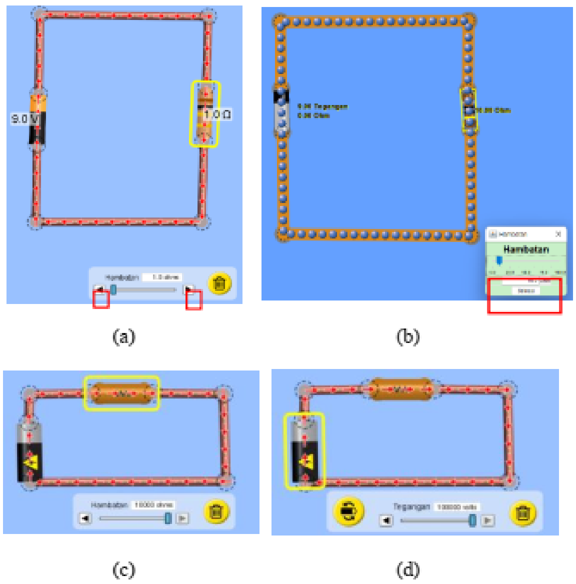


Fig. 9. Display of battery and resistor components in (a) PhET online (b) PhET Offline; (c) Resistor setting for high voltage circuit; (d) Voltage setting for high voltage circuit.

PhET can help make it easier for students to carry out practicums flexibly without a real laboratory [24] and minimize the use of numerous wires within the project [25] because a simulator is an approach that produces promising observations in a non-laboratory environment [26]. PhET bridges the gap between students to the educators [27]. This research has successfully analyzed the interactivity and availability aspects of both types of PhET.

V. Conclusion

In conclusion, PhET is a simulator that is accessible and interactive due to its ability to display the components' conditions experiencing overvoltage. Furthermore, it is a tool for learning basic electronic circuits for students, such as voltage divider circuits, series, and parallel resistors, bridges Wheatstone, Star – Delta resistors, proof of Kirchoff's Laws I and II, and Mesh circuits (2−−3 loops). This claim was confirmed from the PhET review based on the technical or suitability between the simulation and the circuit theoretical calculations results, as well as its ability to operate in a branching circuit. The availability and interactivity aspects show a simple and attractive appearance of PhET, which is quite accurate in performing computations with an average difference of 0.1 to 0.01.

The circuit used in the experiment only involves resistors and voltages arranged in familiar electronic circuits. Meanwhile, measurements are limited to the parameters of the voltage and electric current flowing in each resistor. Further research is needed for complex circuits, such as those involving active components, including PhET exploratory studies to measure electric power, frequency, and several other quantities. Overall, PhET can also be used as an alternative for basic electronics practicum learning for undergraduate students assuming the circuit only requires passive components such as resistors and a DC voltage source from a battery.

REFERENCES

[1] L. M. Ambarita, N. M. S. Hutapea, I. Y. Sitinjak, J. Damanik, H. Sitinjak, and W. Sitinjak, "Peranan pendidikan tinggi dalam mempengaruhi perekonomian masyarakat (kajian aspek hukum dan bisnis)," *Community Development Journal: Jurnal Pengabdian Masyarakat*, vol. 3, no. 2, pp. 1047-–1051, 2022, doi: 10.31004/cdj.v3i2.5319.

[2] F. Rillotta, C. Gobec, and C. Gibson-Pope, "Experiences of mentoring university students with an intellectual disability as part of a practicum placement," *Mentoring & Tutoring: Partnership in Learning*, vol. 30, no. 3, pp. 333-–354, 2022, doi: 10.1080/13611267.2022.2070991.

[3] S. Suwardi, L. Lidiawati, and E. Ayatullah, "Rancang bangun data logger suhu dan kecepatan arus laut untuk praktikum oseanografi," *Jurnal Pengelolaan Laboratorium Pendidikan*, vol. 4, no. 2, pp. 57-–65, 2022, doi: 10.14710/jplp.4.2.57-65.

[4] S. Hamidani, R. Yanto, V. Amalia, and E. Etriyanti, "Pelatihan penerapan media pembelajaran daring dalam upaya peningkatan kompetensi guru sekolah dasar islam terpadu Al-Ikhlas," *Jurnal Abdi Masyarakat Indonesia*, vol. 2, no. 1, pp. 119-–124, 2022, doi: 10.54082/jamsi.171.

[5] R. Ridwan, M. Nurmanita, and N. M. Sangi, "Efektivitas pembelajaran simulasi proteus 8 professional berbantuan virtual laboratory untuk meningkatkan berpikir kritis mahasiswa praktek instalasi listrik," *Journal on Teacher Education*, vol. 3, no. 3, pp. 53-–64, 2022, doi: 10.31004/jote.v3i3.4379.

[6] A. L. Suban, I. D. Reja, and H. Y. M. Doren, "Optimalisasi pemahaman materi rangkaian logika menggunakan metode direct instruction dan perangkat bantu simulasi circuit wizard," *Increate-Inovasi dan Kreasi dalam Teknologi Informasi*, vol. 6, no. 1, pp. 29-–36, 2021.

[7] E. B. Moore and K. K. Perkins, "Advances in PheT interactive simulations: interoperable and accessible," in *Cyber-Physical Laboratories in Engineering and Science Education, Eds. Cham: Springer International Publishing*, 2018, pp. 141-–162. Accessed: Dec. 15, 2022. [Online]. Available: https://doi.org/10.1007/978-3-319-76935-6_6

[8] A. P. Rezky, "Literatur review praktikum fisika pada masa pandemi covid-19," Diploma, UIN Raden Intan Lampung, Lampung, 2022. Accessed: Dec. 15, 2022. [Online]. Available: http://repository.radenintan.ac.id/21422/

[9] M. M. Arifin, S. B. Prastowo, and A. Harijanto, "Efektivitas penggunaan simulasi phet dalam pembelajaran online terhadap hasil belajar siswa," *Jurnal Pembelajaran Fisika*, vol. 11, no. 1, pp. 16-–27, 2022, doi: 10.19184/jpf.v11i1.30612.

[10] A. Fitri, "Laboratorium virtual dengan aplikasi PheT untuk memperkuat penguasaan konsep listrik dinamis siswa pada pembelajaran online," *Jurnal Eksakta Pendidikan (JEP)*, vol. 6, no. 1, pp. 52-–60, 2022, doi: 10.24036/jep/vol6-iss1/624.

[11] R. Haryadi and H. Pujiastuti, "PhET simulation software-based learning to improve science process skills," *J. Phys.: Conf. Ser.*, vol. 1521, no. 2, p. 022017, 2020, doi: 10.1088/1742-6596/1521/2/022017.

[12] I. I. Salame and J. Makki, "Examining the use of PheT simulations on students' attitudes and learning in general chemistry II," *INTERDISCIP J ENV SCI ED*, vol. 17, no. 4, p. e2247, 2021, doi: 10.21601/ijese/10966.

[13] H. Triza, "Kegiatan Bongkar Pasang melalui Aplikasi Phet Virtual Laboratory pada Listrik Dinamis," Progressive of Cognitive and Ability, vol. 1, no. 2, pp. 50-–59, 2022, doi: 10.56855/jpr.v1i2.33.

[14] A. Paul, "Going deeper with PhET interactive simulations," in *Proceedings of the IUPAP International Conference on Physics Education 2022*, Online, 2022, pp. 45-–45. Accessed: Dec. 15, 2022.

[15] K. J. O. Candido, K. C. C. Gillesania, J. C. Mercado, and J. M. B. Reales, "Interactive Simulation on Modern Physics: A Systematic Review," 1, vol. 3, no. 8, pp. 1452-–1462, 2022, doi: 10.11594/ijmaber.03.08.08.

[16] T. Sujatitham and J. Tanamatayarat, "Remote learning on DC circuit analysis by using the sets of video demonstrations and PhET simulations for preparing readiness of pre-service teachers," in *Proceedings of the IUPAP International Conference on Physics Education 2022*, Online, 2022, pp. 157–157. Accessed: Dec. 15, 2022. [Online]. Available: https://openjournals.library.sydney.edu.au/ICPE/article/view/16401

[17] W. Pratiwi, S. Fuada, F. W. Zanah, and N. Restyasari, "Analisis rangkaian wheatstone bridge menggunakan simulator circuit wizard, proteus, dan multisim," *Telecommunications, Networks, Electronics, and Computer Technologies (TELNECT)*, vol. 1, no. 1, pp. 1-–13, 2021.

[18] M. S. D. Utomo et al., "Analisis perhitungan teori dengan menggunakan variasi simulator online pada rangkaian pembagi tegangan," *Telecommunications, Networks, Electronics, and Computer Technologies (TELNECT)*, vol. 1, no. 2, pp. 61-–70, 2021.

[19] S. Fuada et al., "Analisis rangkaian pembagi tegangan dan perbandingan hasil simulasinya menggunakan simulator offline," *CIRCUIT: Jurnal Ilmiah Pendidikan Teknik Elektro*, vol. 6, no. 1, pp. 28-–46, 2022, doi: 10.22373/crc.v6i1.11200.

[20] F. Ajredini, A. Gjevori, N. Izairi, K. Rasimi, and O. Zajkov, "PhET simulations vs real experiments for better understanding electrical resistance," *European Journal of Physics Education*, vol. 5, no. 3, pp. 59-–70, 2013.

[21] F. Ajredini, N. Izairi, and O. Zajkov, "Real experiments versus phet simulations for better high-school students' understanding of electrostatic charging," *European Journal of Physics Education*, vol. 5, no. 1, pp. 59-–70, 2017, doi: 10.20308/ejpe.v5i1.63.

[22] J. Park and H.-G. Yoon, "Inquiry of the parallel connection of batteries by using PhET simulation: How can simulation help pre-service elementary teachers to understand anomalous situation?," *New Physics: Sae Mulli.*, vol. 72, no. 5, pp. 376-–389, 2022, doi: 10.3938/NPSM.72.376.

[23] I. Ismalia, M. Kusumawati, and P. Wahyuni, "Investigating the use of PhET simulation as a substitute for practical tools in understanding the concept of static electricity," *International Journal of Education and Teaching Zone*, vol. 1, no. 1, pp. 20-–25, 2022, doi: 10.57092/ijetz.v1i1.7.

[24] H.-T. Wu, K. Mortezaei, T. Alvelais, G. Henbest, C. Murphy, E. J. Yezierski, and J. F. Eichler, "Incorporating concept development activities into a flipped classroom structure: using PhET simulations to put a twist on the flip," *Chemistry Education Research and Practice*, vol. 22, no. 4, pp. 842-–854, 2021, doi: 10.1039/D1RP00086A.

[25] K. S. Tuyboevna, "About the use of interactive method and phet electronic resource in educational process," *Mid. Eur. Scin. Bul.*, vol. 2, no. 1, pp. 49-–54, 2021, doi: 10.47494/mesb.2021.2.164.

[26] T. Juwariyah and Y. Djaja, "Analisa resistivitas kawat penghantar ditinjau dari metode jembatan wheatstone dan metode hukum ohm pada modul praktikum fisika," *Bina Teknika*, vol. 12, no. 2, pp. 23–244, 2017, doi: 10.54378/bt.v12i2.79.

[27] M. G. Saudelli, R. Kleiv, J. Davies, M. Jungmark, and R. Mueller, "PhET simulations in undergraduate physics: Constructivist learning theory in practice," *Brock Education Journal*, vol. 31, no. 1, pp. 52-–68, 2021, doi: 10.26522/brocked.v31i1.899.