ISSN 0511-5728
The West Indian Journal of Engineering
Vol.40, No.2, January/February 2018, pp.17-24

The Development of a Portable Electrical Engineering Educational Outreach Toolkit

Keishan Narinesingh[a, Ψ], Sanjay Bahadoorsingh [b], and Chandrabhan Sharma [c]

Department of Electrical and Computer Engineering, Faculty of Engineering, The University of the West Indies, St. Augustine, Trinidad and Tobago, West Indies;
[a]E-mail: keishan.narinesingh@my.uwi.edu
[b]E-mail: Sanjay.Bahadoorsingh@sta.uwi.edu
[c]E-mail: Chandrabhan.Sharma@sta.uwi.edu

[Ψ] *Corresponding Author*

(Received 30 June 2017; Revised 29 November 2017; Accepted 04 December 2017)

Abstract: *A strong STEM (science, technology, engineering and mathematics) workforce is central to economic growth and development. To build such a workforce, there is need to promote STEM disciplines. This paper describes the use of a portable electrical engineering outreach toolkit that targets primary and secondary students. The Outreach Toolkit contains 1) a Van De Graff Generator, 2) Tesla Coil, 3) Joule Thief and 4) a Combinatorial Logic Designer Board. Based on the electrical engineering theory and principles as required by the primary and secondary school curricula, live demonstrations are to be conducted using these devices. Complemented with the Toolkit, there are user manuals and a suite of videos that describe various experiments, safety precautions and maintenance requirements. For evaluating the efficacy of the toolkit, a group of 1 primary and 1 secondary schools from the South Eastern Education District of Trinidad and Tobago was based, and their students and teachers were invited to participate a demonstration of the toolkit. Results showed that majority of the secondary school students (90%) indicated that the use of the toolkit could increase their interests in studying science. Some 95% of students indicated that the toolkit made learning science more fun and motivational, and would like to have the device equipped at their school.*

Keywords: *STEM, Combinatorial Logic Designer Board, Educational Outreach Toolkit, Trinidad and Tobago*

1. Introduction

There is a pressing need for the Caribbean to embrace STEM (science, technology, engineering and mathematics) education to boost interest in sciences, encourage the pursuit of jobs in science and engineering and promote awareness of the link between science/engineering and regional economic development (Foundation, 2015). Encouraging young people to pursue a career in engineering is paramount to developing a strong STEM workforce. Such a workforce would address regional challenges such as energy sustainability, food security and economic decline. Educational outreach refers to activities that support formal and/or classroom-based education, as well as informal education that occurs outside the classroom (Education, 2002).

It has been widely argued that informal forms of education could boost interest in learning, in conjunction with formal education. Educational outreach is beneficial for a number of reasons. For instance,

- Students who struggle in a formal school setting may blossom in an informal setting.
- Informal education could boost students' confidence in a classroom setting.
- Teachers tend to adhere to a fixed curriculum in the classroom (formal setting) whilst out of the classroom programmes (informal setting) allow more flexibility with content.

In order to engage primary and secondary school students in science, live demonstrations are effective (Differently, 2013). This paper describes the development of a portable electrical engineering educational outreach toolkit that can be used encourage primary and secondary school students in science, particularly electrical engineering. The outreach toolkit comprises four devices, these are: 1) the Joule Thief, 2) a Van De Graff Generator, 3) a Combinatorial Logic Designer Board, and 4) a Tesla Coil. Based on the electrical engineering theory and principles as required by the primary and secondary school curricula, live demonstrations are to be conducted using these devices. For example, a school teacher could use the Van De Graff Generator to demonstrate the principles of electrostatics (see Table 1).

Each device in the outreach toolkit is accompanied with a set of user-friendly manuals and videos, which describe various experiments that can be performed. For facilitating these experiments, a set of Teachers' notes for each experiment is also provided. In addition, the user manual outlines safety precautions and maintenance tips for each device. This paper describes the design of the toolkit, presents test results and assesses the cost of producing the toolkit.

Table 1. Topics addressed by each device of the outreach toolkit

Device	**Topics addressed**.
Van De Graff Generator	Electrostatics, charging by induction and conduction, triboelectric series, Faraday's ice pail effect, types of charges and force on charge in electric field.
Joule Thief	Transistor operation as a switch, charging and discharging of inductors, LED electrical characteristics, introduction to boost converter, voltage clamping using diodes, and capacitive smoothing.
Tesla Coil	Electric fields, florescent lamp operation, flux linkage, transformer operation.
Combinatorial Logic Designer Board	Operation of the fundamental logic gates, operation of flip flops, half adder, full adder and three bit binary counter, counting in binary, converting between binary and decimal, switch bouncing, conductivity of the human body, conductors and insulators.

2. Devices in the Outreach Toolkit

2.1 Van De Graff Generator

Description

A Van De Graff (VDG) generator is a machine used to generate a high DC voltage by moving charge from a source to an isolated dome via a rotating belt (see Figure 1). This device is to conduct various electrostatic experiments (see Table 1).

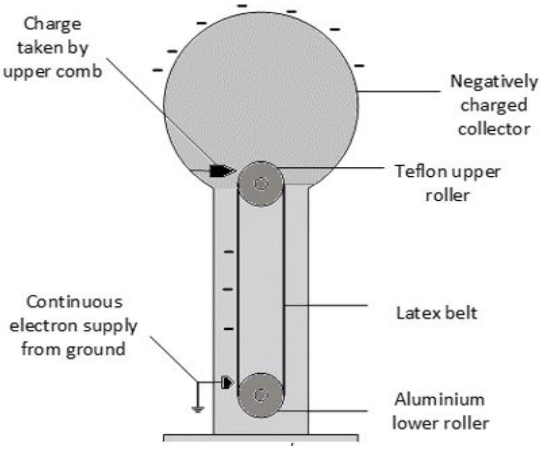


Figure 1. Generic Van De Graff generator

Operation

The Triboelectric series lists the materials that would become most positive or negative when in contact with another material (EESemi, 2001). This series is used decide on which materials for the upper and lower rollers. Roller materials are chosen as far apart on the Triboelectric series to achieve maximum static charging. The operation of the Van De Graff generator is explained as follows:

1) Charging the lower roller:
The AC motor is powered from a 110 V supply. As the belt revolves around the upper and lower rollers, the surface of the lower roller becomes charged by the frictional charging between the roller and the belt. The quantum of charge developed by the roller and the belt depends on where the materials are on the triboelectric series. In this explanation it is assumed that the lower roller has a greater tendency to become positive. As the belt continues to rotate and charge the lower roller there is a resulting charge imbalance. This occurs since the electrons from the roller moves onto the belt. Therefore, the roller becomes positive and the belt becomes negatively charged. The positively charged roller now attracts the electrons from the grounded lower comb and the process of charge movement repeats.

2) Charges move across the air:
This attraction causes electrons to concentrate at the tip of the lower comb. As the belt continues to rotate and charge the lower roller, the electric field between the belt and comb tips becomes strong enough to separate the electrons and the nuclei of the surrounding air molecules. This results in a conductive path known as corona discharge or plasma. Electrons from the plasma stick to neutral air molecules giving them a net negative charge. The negative comb repels the negative air molecules. This results in a negatively charged wind (ion wind) emanating from the comb.

3) Charges are caught by the belt:
The conductive path caused by the corona discharge allows for the ion wind to move in the direction of the positively charged lower roller. The belt intercepts the ion wind thereby increasing the negative charge of the belt. As the belt rotates, negative charges are constantly sprayed on the rubber belt. The lower comb is grounded. Therefore, there is a continuous supply of negative charge.

4) The belt carries charge to the upper roller:
The negatively charged belt rotates to the top roller near the upper comb. The electrons in the tip of the upper comb are repelled by the strong negative charge of the belt and positive charge accumulates at the tips of the comb. This creates a strong electric field between the belt and the upper comb, which causes corona discharge. The free electrons resulting from the discharge is attracted to the positive comb tips. The positive air molecules are attracted to the negatively charged belt, thus neutralising the belt.

5) Charges exit at the top comb to the dome
The upper comb is electrically connected to the collector. As the belt repels more electrons into the upper comb the charges distribute evenly on the outer surface of the

collector. In this way, the collector continues to accumulate negative charge as the belt rotates.

2.2 The Tesla Coil

Description

A tesla coil was a device invented by Nikola Tesla in 1831. The device utilises a resonant air-core transformer circuit to produce a high voltage, low current and high frequency AC current. Voltages over one million volts could be generated, and are discharged from the toroid (top load) of the tesla coil in the form of sparks. For this project, the Tesla Coil is a solid-state device and does not require capacitor banks or a spark gap to produce oscillations. This low-power and compact device utilises a transistor to control the resonance of the primary and secondary coils. Figure 2 shows the circuit design of the Tesla coil, named as the Slayer Exciter (Sadaghdar, 2015). Both J. Stiffler and G. Bluer of the United States were the inventor of this version of the Tesla Coil. This device can be used to demonstrate Faraday's Law and the existence of electric fields (see Table 1).

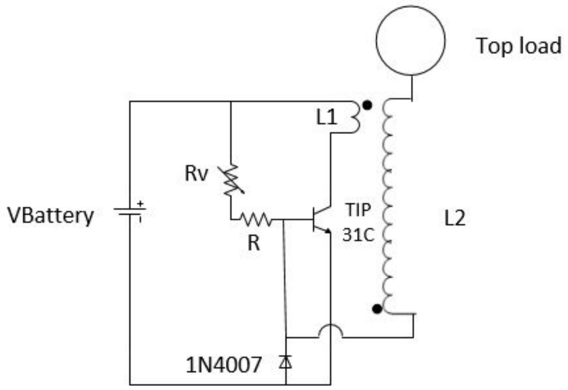


Figure 2. Slayer Exciter circuit diagram
Source: Adopted from Sadaghdar (2015)

Operation

Operation of this circuit starts when the switch is closed (switch not shown in the diagram). At this instance, the transistor's state is 'off'. Therefore, the current through the primary coil L_1 is zero and the voltage induced across the secondary coil L_2 is zero.

As the transistor turns on, the current of the collector increases and it flows through the primary coil, creating an increasing magnetic field. The magnetic field of the primary induces a voltage across the secondary such that the top-load is positive. Due to the voltage of the top-load, there exists an associated electric field. The negative voltage induced at the bottom of the secondary forces the base of the transistor low, turning off the transistor. Since there is no current flow through the primary coil, its magnetic field collapses. Hence, the secondary magnetic field also collapses.

At this stage, current starts flowing into the base of the transistor again and the process repeats. This process repeats at a frequency in the order of kilohertz. The system is always in resonance, since the transistor will only turn back on when the secondary coil magnetic field has collapsed.

2.3 Joule Thief

Description

A Joule thief is a circuit that uses an AA battery with a voltage ranging between 0.75 V and 1.5 V and is able to power multiple LEDs. The circuit was invented by Z. Kaparnik of the United Kingdom (Kaparnik, 1998), and it first iteration was named as 'One Volt LED-A Bright Light'. Kaparnik presented three variations of his circuit for operating LEDs from a supply below 1.5 V. In 2002, Clive Mitchell named his variation of Kaparnik's design 'The Joule Thief'. His variation was different only in terms of component values. This device can be used to demonstrate series/parallel connections and charging/ discharging of inductors.

Operation

Figure 3 shows the circuit design for the Joule Thief that was adapted from Kaparnik (1998). With the power switch on (not shown), current flows through the primary winding, L_1, through resistor, R, and into the base of the transistor. The transistor begins to turn on. Therefore, current starts to flow through the secondary windings, L_2. The cathode of the diode is more negative than the anode, but the diode will not light since the battery voltage is a maximum of 1.5 V, while the led typically requires 2.0 V to light. Therefore, no current flows through the LED.

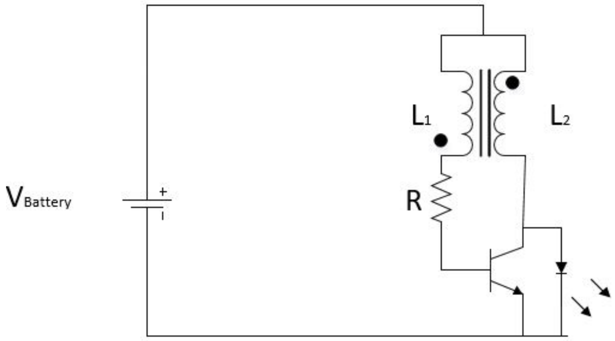


Figure 3. Joule Thief circuit diagram
Source: Adapted from Kaparnik (1998)

The current through the secondary coil (L_2) is larger than that through the primary (L_1). The interaction between the magnetic fields of L_1 and L_2 creates a positive feedback system between the coils. This increases the current through $L_{2,}$ creating a stronger magnetic field which induces an emf across L_1, resulting in an increased base current to the transistor. This increase in base current causes the current through L_2 to increase, continuing the positive feedback process.

This process continues until the inductor core or transistor reaches saturation, if either saturates there cannot be any further increase in magnetic field strength. Since there is no changing magnetic field, there will not be an induced voltage across L_1. This causes a voltage to be generated across L_1 in a direction to oppose the source. The base current drops and the transistor enters the cut off region.

Since the transistor is now off, the L_2 magnetic field collapses. This would generate a voltage spike that appears across the LED, forward biasing it and the LED lights. Once the magnetic field of L_2 collapses, current starts flowing through L_1 again into the base of the transistor, and the positive feedback process restarts. It shows that the LED is not always on, but instead flashes at a fast rate so that the brain perceives it as always being on.

2.4 Combinatorial Logic Designer Board

Description

The Combinatorial Logic Designer Board is a hands-on device that allows the user to build various digital circuits. The board features logic circuits required by the CXC and CAPE syllabi. These circuits include, *T* flip-flop, *SR* flip-flop, 3-bit binary adder using *T* flip-flop, half adder and full adder. The board also allows for custom-built circuits. Input is via push button switches, slide switches and a light sensor. Output devices are LEDs, seven segment displays and a buzzer. One use of the Logic Board is to demonstrate conductivity of the human body, counting in binary and the conversion between binary and decimal.

Operation

The Combinatorial Logic Designer board consists of four main sections that can be interconnected using banana plugs. These sections are as follows:

1) User input section: The user is able to choose between push buttons, slide switches or a light sensor as the input stimulus.

2) Logic gates: The user is able to verify the logic gate truth table (NOT, OR, NOR, AND, NAND, and XOR) by observing its input/output characteristics.

3) Circuit selection field: The user selects a circuit to be explored, for example, the 3-bit binary counter or the half adder. The user can choose any form of input for the selected circuit. Inputs are fed to the selected circuit using banana plugs.

4) Output: This section contains the devices that will respond to the signals received from the selected circuit. The signaling section consists of a seven-segment display, LEDs and a buzzer.

3. Design of the Toolkit

3.1 The Van De Graff Generator

The Van De Graff generator was designed in part using design recommendations made by Beaty (1996), Graff (2008) and Ritchey (2010). The design utilised a 12-inch sphere which could generate a maximum voltage of 360 000 V. Figure 4 presents a demonstration of operating the Van De Graff Generator.

Figure 4. Operating Van De Graff Generator

The following is a summary of the design specifications for the VDG:

- Largest collector is used to maintain portability of the outreach toolkit (i.e., 12-inch aluminum gazing ball).
- 6.35 cm wide latex rubber used for belt.
- Adjustable speed motor (1,000 rpm max)
- Distance between the collector and base is at least twice the radius of the collector.
- Collector is highly polished
- Aluminum lower roller
- Teflon upper roller
- PVC column (26 inch)
- VDG mounted on Plywood base

3.2 Joule Thief

Figure 5 shows the Joule thief circuit design that is adapted from Kaparnik (1998). A 1.5 V AA battery would be needed to turn on a LED of the device. Figure 5 shows a completed Joule Thief. The design specifications for the Joule Thief are determined. These are summarised as follows:

- Center tap transformer is to be created with twenty turns of 32 AWG enamel wire on both the primary and secondary coils.
- Ferrite core is to be obtained from a compact fluorescent lamp.
- 2N3904 Transistor is used for high current gain and low cost.
- Designed to turn on a LED with a supply battery voltage of at least 1 V.

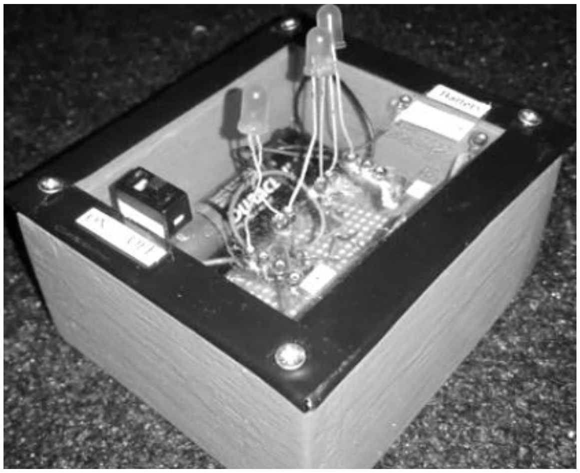


Figure 5. Completed Joule Thief

3.3 Tesla Coil

Figure 6 depicts the Tesla Coil circuit design that is adapted from Sadaghdar (2015). The Tesla coil was designed to light a fluorescent lamp wirelessly from as far as possible, while maintaining portability. The fluorescent lamp lights wirelessly because of the changing electric field produced by the secondary coil. Therefore, a larger secondary voltage would increase the range of the Tesla Coil. Since the current through the primary coil, L_1, and the turns ratio directly affect the voltage across the secondary coil, these variables were set to maximum, while maintaining safety and portability requirements.

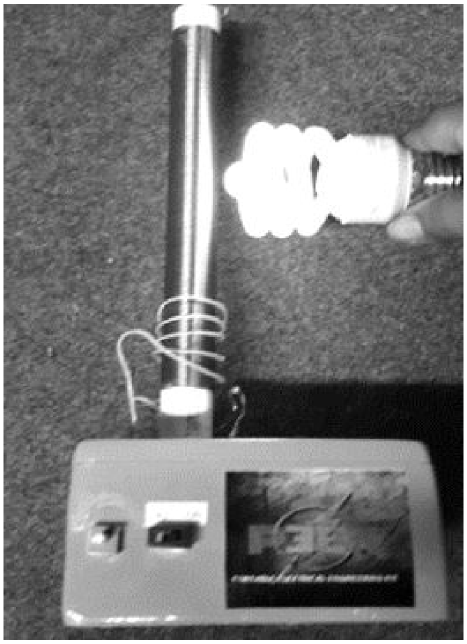


Figure 6. Operating Tesla Coil

The design specifications are determined for the Tesla Coil. These are summarised as follows:

- TIP31C transistor is to be used for high power and switching frequency capability.
- For safety, the current through the primary coil is to be set to the maximum value (400 mA).
- The turns ratio is to be set to a maximum value while maintain portability (Max secondary coil length = 18 cm).
- Variable resistor is to be added to the base of the transistor to allow power level adjustments of the Tesla Coil.
- 18 V source supply voltage.

3.4 Combinatorial Logic Designer Board

The Logic Board is powered with a 9-V battery, and all ICs used have identical electrical characteristics (i.e., V_{OL}, V_{OH}, V_{IL}, $V_{IH,}$ and V_{DD}). This allows for direct integration of the ICs. The Logic Board consists of the following sections: Inputs, 3-bit counter, Adders, Logic Gates, Flip-flops and outputs. Figures 7 and 8 show a completed Logic Board, and the Block diagram of the Logic Board circuitry, respectively.

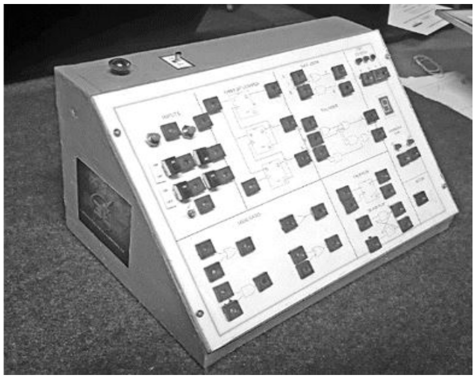


Figure 7. Completed Logic Board

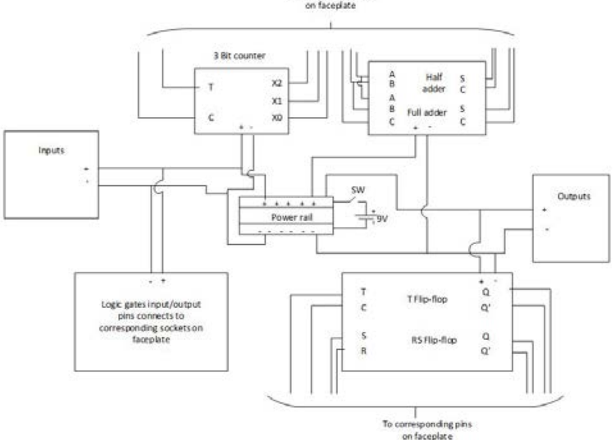
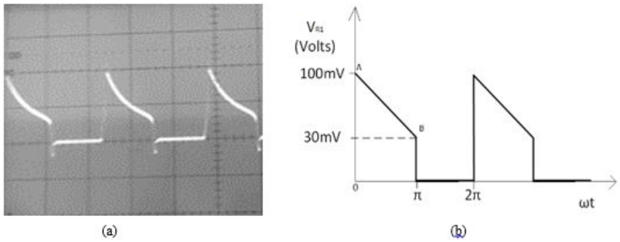


Figure 8: Block diagram of the Logic Board circuitry

4. Results and Functionality of the Devices

The Logic Board passed various unit and integration tests. The user manual provides a brief description of the Logic Board's origins precautions for using the board and the procedure for conducting seven unique experiments. From the results obtained, the Joule Thief was able to turn on a 1.80 V LED using a minimum supply voltage of 0.87 V. Using a 1.50 V battery and loaded with one LED and a 1Ω current sensing resistor (R1), results are recorded. Figure 9(a) and 9(b) show the actual output waveform obtained, and give the corresponding designed output current expected, respectively.



(a) (b)

Figure 9. Output current waveform

Equation of line

$$AB = \frac{70\times10^{-3}}{-\pi}\,\omega t + 0.1 \tag{1}$$

Average voltage across R_1,

$$V_{R1} = \frac{1}{2\pi}\int_0^{\pi}\frac{70\times10^{-3}}{-\pi}\,\omega t + 0.1 \quad \omega t \tag{2}$$

$$= 32.50mV$$

Average output current, $I_{avg} = \frac{V_{R1}}{R_1}$ $= 32.50mA$

The average output current is 32.50 mA and average output power is 21.678 mW.

There are three experiments provided in the user manual. The Tesla coil Slayer Circuit is able to light a fluorescent lamp held approximately 7 cm away from the secondary coil. This range is satisfactory.

The VDG is able to achieve an average collector voltage of 153 kV. The arc length is measured by slowly moving a discharge wand towards the collector and measuring the distance between the collector and wand at the point of arcing (collector is allowed to charge for 30 seconds between discharges). The estimated voltage developed, V_D, is calculated using equation 3, where the arc length is in centimetres:

$$V_D = Arc\ length \times 30\ kV \tag{3}$$

Moreover, it is recommended that the VDG be operated in a low humidity environment for best results. The average arc length is 5.1 cm, and hence, the average developed voltage, V_D, is 153 kV. Table 2 provides a summary of number of experiments and the performance of respective devices.

Table 2. Performance summary of the devices

Device	Performance	Number of experiments
VDG	Average developed voltage = 153 kV.	5
Tesla Coil	Range of at least 7 cm	3
Joule Thief	Average output current 32.50 mA.	4
Logic Board	All circuits are functional.	7

5. Outreach Toolkit Demonstration

For evaluating the efficacy of the Portable Electrical Engineering Educational Outreach toolkit, it was taken to one primary and one secondary school in the, South Eastern Education District of Trinidad and Tobago. Feedback from students and teachers from both schools is collated and analysed.

5.1 Primary School Feedback

1) From Students

A demonstration session of the toolkit was made to students of the Standard four and five at the school. Students were eager to investigate the devices. For instance, they asked questions about the Van De Graff Generator, such as: "*Would current flow through your body if three persons were holding hands and only one was touching the collector*?" A student was able to suggest that an electromagnetic wave from the Tesla Coil caused the fluorescent lamp to light.

At the end of the session, students showed keen interests and would like to have the device equipped at their school. Figure 10 shows a photo taken of the primary school students investigating the VDG.

Figure 10. Primary school students investigating the VDG

2) From Teachers:

The Session received positive feedback from teachers who attended the session. Most teachers expressed that the outreach toolkit would be a valuable tool for engaging students in science, and requested periodic demonstrations at their school, at all levels.

5.2 Secondary School Feedback

1) From Students:

A group of 45 students (from both Form 3 and Form 6) were present for the demonstration session of the toolkit. Before the start of the session, a set of standard questionnaires about the toolkit were provided. The questionnaire had two parts, requiring students to answer pre-demonstration and then post-demonstration questions.

From the pre-demonstration data and results, 55% of the students indicated they were interested in pursuing science, while 30% and 15% were interested in Business and General Studies, respectively. Students thought that performing science experiments would be fun. From the post-demonstration data and results, all students shared their views that the presentation was very interesting (75%) and was interesting (25%). Moreover, a majority (some 90%) of the students indicated that the use of the toolkit could increase their interests in studying science. Some 95% of students indicated that the toolkit made learning science more fun and motivation, and would like to have the device equipped at their school.

2) From Teachers:

Physics teachers expressed a great need for the outreach toolkit at their school after seeing how engaged the students were during the demonstration. Comments received include:

- *"The outreach toolkit is ideal for prompting students to think outside the box and become engaged in scientific discussions."*
- *"It makes the students want to learn more, since they are fascinated by the devices."*
- *"The smiles I saw on your faces, I do not know what I am going to do without this equipment."*

6. Financial Assessment

Figure 11 shows a sample set of the Outreach Toolkit housed in the carrying case. An attempt was made to address the financial implications in making/equipping such a Toolkit. One experienced person had already gone through the learning curve, and taken up the task to make/construct the sample toolkit. The expected time for construction of the Toolkit was calculated neglecting delays (time for paint/glue to dry and breaks). Within the limits of the assumptions made, the estimated time for construction of the Toolkit is 47.50 hours.

Figure 11: Devices housed in the carrying case

The material cost for the toolkit (excluding labour costs) to produce the Toolkit is amounted approximately TT$2,000.00 per unit (i.e., TT$1,866.60 + 136.04 = TT$2,002.64 or US$318.90; Exchange Rate: US$1.00 ≈ TT$6.30). Table 3 shows a summary of a preliminary financial assessment for the Toolkit.

An equivalent Outreach Toolkit is not commercially available. Only similar Van De Graff Generators and Tesla coils are commercially available but cost 105% and 137% more than the devices in this paper respectively. The carrying case is custom built to house the items in the Toolkit, therefore the carrying case is not commercially available. It is expected that if the Toolkit is accepted in schools, the manufacturing costs would drop significantly using economies of scale.

7. Conclusion

The Toolkit is an educational tool used to conduct live demonstrations electrical engineering theory and principles as required by the primary and secondary school curricula. It consists of four devices, with accompanying user manuals and accessories. The material cost of the toolkit is approximately $2,002.64, and the estimated time for construction is 47.50 hours. The Joule Thief, Tesla Coil and the Combinatorial Logic Designer Board performed satisfactorily. These devices are equipped to conduct a list of experiments described in the user manual.

Table 3. Summary of financial assessment for the Outreach Toolkit

Device	Cost to construct (TT$)	Cost for manual and accessories (TT$)	Labour hours required
Van De Graff generator	998.80	34.00	16.00
Tesla Coil	54.05	55.00	4.00
Logic Board	245.75	25.00	12.00
Joule Thief	42.04	22.04	3.50
Carrying case	568.00	0.00	12.00
Totals	**$1,866.60**	**$136.04**	**47.50 hours**

Based on the feedback from the school visits and demonstration session, both Primary and Secondary school teachers indicated that the outreach toolkit would be an asset to their school as it provides a mechanism to engage students in scientific experiments that are both fun and educational. Majority of the secondary school students indicated that the outreach kit made learning science more fun, and enhanced their interests in learning. Some 95% of students who attended the session would like to have the device equipped at their school. Primary school students were equally excited and engaged in the demonstration sessions. The Toolkit would thus be an essential item in the laboratories at schools. It would be suggested the Ministry of Education to consider the Toolkit as one of the essential tools for engaging students in science learning through experimentation.

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Authors' Biographical Notes:

Keishan Narinesingh *is an Electrical and Computer Engineering graduate from The University of the West Indies. His undergraduate special project focused on designing and producing an Electrical Engineering Outreach Toolkit for exciting young people in learning about science. His interests includes power system operations, control/planning and educational outreach.*

Sanjay Bahadoorsingh *completed his B.Sc. degree from The University of the West Indies and the M.Sc. degree from UMIST. He completed the Ph.D. degree at The University of Manchester and is currently a Senior Lecturer in the Energy Systems Group at The University of the West Indies, St Augustine. Dr. Bahadoorsingh has published extensively in power systems operation and planning, renewable energy, smart grid, asset management and dielectric ageing.*

Chandrabhan Sharma *is Professor of Energy Systems with the Faculty of Engineering, The University of the West Indies. He is the Head of the Centre for Energy Studies and the Leader of the Energy Systems Group. Professor Sharma has served as a member of the Board of Directors of the local Electric Utility for over 10 years, and is a member of the Board of Directors of the largest bank in the country. Prior to joining the academic staff at the university, he was attached to the petrochemical industry in Trinidad. His interests are in the area of power system operations and control.*

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