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Low-cost experiments for teaching eletrostatics in Brazilian high school

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Abstract

Many public schools in Brazil do not have the financial resources to obtain certain equipment for teaching physics. Considering that the Brazilian National Common Curricular Base, a normative document that defines the organic and progressive set of essential learning that all students must develop, determines that the curriculum for teaching electromagnetism for high school encompass electrostatics. It is very important that schools offer laboratory conditions. For this reason, it was proposed to design simple and low-cost construction equipment, so that teachers from the basic education network can build them for their schools, thus improving the quality of teaching for their students. This study aims to gather equipment and experiments, such as electroscope, electrophorus, Leyden jar and Van de Graaf generator, which can be used in the classroom for didactic purposes in physics teaching. The main focus of this work is the construction of equipment for the implementation of a laboratory for the study of electrostatics, which addresses physical concepts seen by high school students of the basic network in Brazil.

Keywords: low cost, electroscope, electrophorus, Leyden jar, Van de Graaf generator, experimental physics teaching

Supplementary material for this article is available online

1. Introduction

In Brazil, the way in which students are admitted to the University is based on written assessments (University Entrance Exam and ENEM-Exame Nacional do Ensino Médio), motivating most professors with a theoretical approach focused on problem solving. However, as the Curriculum Reference for High School provides, the teaching of Physics must go further

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and seek to contextualize the contents with a language accessible to students. The document also places the teacher's knowledge in experimental didactics as a fundamental to achieve a more complete learning of the students. In addition, researchers [1, 2] consider the experimental teaching of Physics as fundamental for the familiarization and construction of Science. Even with its widely recognized importance, the experimental teaching of Physics is still very uncommon in schools. The first and most relevant factor is the lack of equipment and funds for teachers to carry out experiments. The second factor is the intrinsic difficulty that some of the practices can cause, such as lack of space, health risks (shocks, burns, etc), external factors (air humidity, turbidity, etc), among others.

Following the guidelines of the BNCC (Base Nacional Comum Curricular), the electromagnetism curriculum for High School [3] is branched into three knowledge objectives: (i) electric field, (ii) circuits and electric energy, (iii) magnetic field. The objective of knowledge related to the electric field includes electrostatics, defined as the branch of Physics (it studies the behaviour of stationary electric charges [4–6]) that encompasses concepts such as electrification processes, Coulomb's law, electric field and potential differences electric.

As a result of these difficulties, physics teachers seek extracurricular mechanisms to overcome the reality in Brazilian schools and bring the experimental teaching of Physics into the classroom. They commonly look for simple and inexpensive experiments that can satisfy the needs of their classes. In searches on the internet and in textbooks [5, 7–11], we find several experiments that promise to be simple and didactic. However, their executions show unforeseen difficulties, either due to failures in the design/instructions, the lack of adequate materials or the infeasibility of taking them to a classroom. In this article we propose four more common experiments in electrostatics, scoring the advantages and disadvantages of each one, as well as detailing the improvements, problem solutions, facilitations and cost reductions found. In section 2, materials and methods will describe the construction of the equipment, followed by section 3 where its operation and possible improvements will be discussed.

2. Materials and methods

2.1. Electroscope

The electroscopes, widely used in the last century, are devices that use the principle of electrification by induction to identify whether or not a material/body is electrically charged. Through measurements made with this instrument, several basic concepts of nuclear and particle physics emerged, such as quantitative measurements of radioactivity and its particles and measurement of elementary electric charge [12, 13].

This equipment, highly recommended for didactic use in the classroom, as a good option for primary school teachers, presents a very simple and low-cost construction and use, having a visual appeal when showing macroscopic phenomena related to the microscopic world. It is an aid instrument for demonstrating the properties involving the electric force and the processes of electrification of materials. It is common to find it in physics teaching materials [14], on various internet sites [15–18], and videos on YouTube [7].

The principle of its operation consists in the movement of electric charges, so that the same charges will repel each other and the different ones will attract each other. So when we bring an electrically charged object close to the top part of the electroscope, it will attract the opposite electrical charges and repel the equal ones away, causing the aluminium sheets to separate due to the accumulation of equal charges in the lower part, as shown in figure 1.

The materials used in this experiment consist of: transparent bottle (glass or plastic); metallic wire (conductive metal); paper or aluminium plate; weight (dry sand for example).

The electroscope equipment montage consists of the following steps:

Step 1: (a) Bend the wire leaving it in the shape of a hook at one end; (b) make a hole in the bottle cap/stopper (with the help of a knife with a sharp tip, a drill, or a hot nail) and pass the wire through it (the wire should fit snugly in the hole); (c) then wind the end of the wire so that it does not come out of the hole, as shown in figure 2(a). The length of the wire will depend on the height of the bottle, the hook must be above half the height of the bottle. The wire can be made of any conducting metal. The easiest to get are: clothesline wire

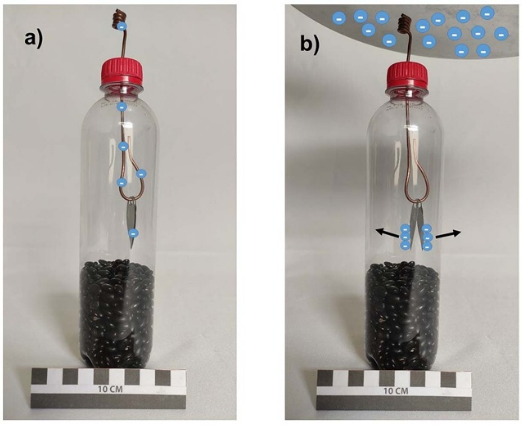

Figure 1. (a) Electroscope without the influence of an electrical charge. (b) Electroscope under the influence of a source of electrical charge.

for hanging clothes and rigid copper wire. They can be purchased at construction material stores, or reused at construction sites.

Step 2: (a) Cut the aluminium foil/ plate so that it has a drop shape; (b) then make a small hole close to the thickest edge of the drop with about three times the diameter of the wire (the hole should be as close as possible to the edge of the drop). Two drops of aluminium foil plate will be needed (figure 2(b)). It is worth mentioning that aluminium foil is a simpler option to make the drops, but it wrinkles very easily. It is important to point out that the sheets of drops should be as flat as possible. So, aluminium foil end up being a better option as they can be made using a recyclable aluminium can. As the aluminium plates will be heavier than the aluminium foil, you should make the drops smaller and more elongated in shape.

Step 3: (a) Hang the aluminium drops on the wire hook; (b) then cap the bottle and adjust so that the drops are halfway up the bottle. The drops must remain inside the bottle as shown in figure 2(c). It is possible to use any recyclable bottle to build the device as long as it is made of a transparent and insulating material. The best option is a 600 ml bottle with a completely smooth surface on the outside, like the bottle in figure 2(c).

Step 4: Place the weight material at the bottom of the bottle so that it does not touch the aluminium drops and can move freely. Let the material dry before placing it in the bottle, as there must be no moisture inside (figure 3). This material is used to make the recyclable plastic bottle stable when standing. If you decide to use a recyclable glass bottle, the weight at the bottom of the bottle will not be necessary. Due to the electrical properties of the water molecule, humidity is a major problem for the proper functioning of the electroscope. Therefore, this weight at the bottom of the bottle must be dry. It is suggested to use marbles or dry seeds (beans or rice for example).

2.2. Electrophorus

The word *electrophorus* was coined by Volta from the Greek, *elektron*, and φέρω, *phero*, meaning ‘electricity bearer’. The electrophore arises from a need to have a simple handling and construction device capable of joining a large amount of electrical charges in a quick and practical way. Materials are generally electrically neutral, i.e. they have an equal number of protons and electrons. However, some processes [19, 20] can cause disparity between the charges, leaving the material electrically charged.

One of these processes deals with electrification by friction, in which two dielectric materials are rubbed against each other, presenting behaviour of loss or gain of electrons. These materials are organized in a table called the triboelectric series [21]. An example of this phenomenon is what happens when we rub a PVC pipe with a woolen jacket. PVC, a material that has a strong tendency to receive electrons, and wool is a material that has a strong tendency to lose them, when rubbed against each other, one will be negatively charged (PVC) while the other will be positively charged (wool), as shown in figure 4.

Another process is contact electrification, in which an electrically charged conducting material touches another initially neutral conducting material, causing the charges to be distributed between them, so that both will be charged with the same charge.

The last process deals with electrification by induction, in which when we approach an electrically charged body to a conductive material, initially neutral, the charges will be separated. Then we can ground the negative charges, or remove part of the charge, by touching the body to a larger body that can absorb or release charges from it.

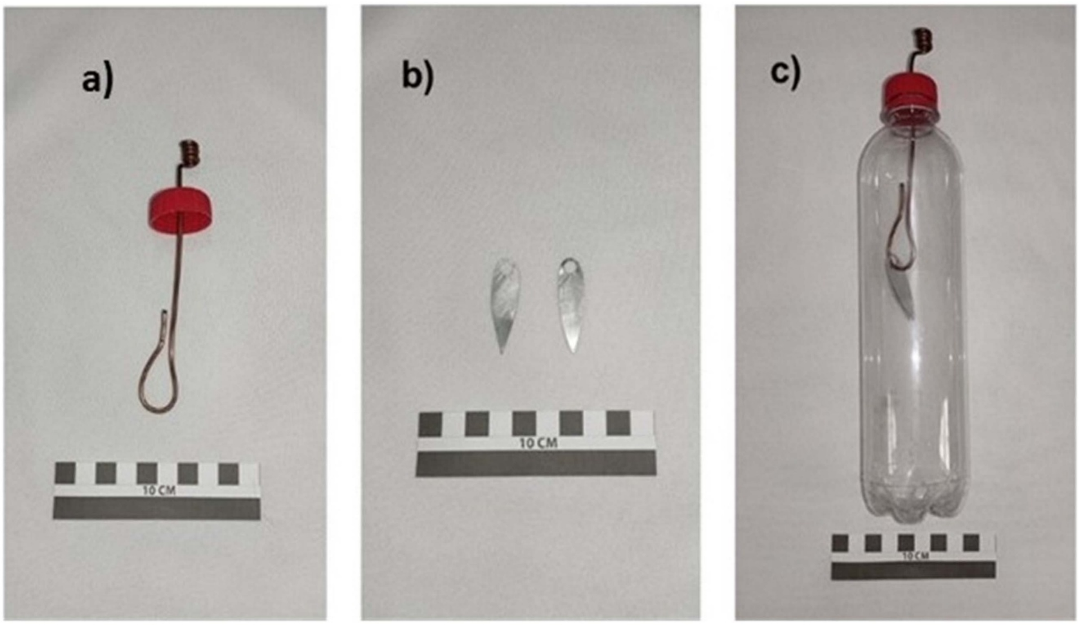

Figure 2. (a) Bent wire fix to the lid. (b) Drop shaped aluminium sheets. (c) Assembled mechanism.

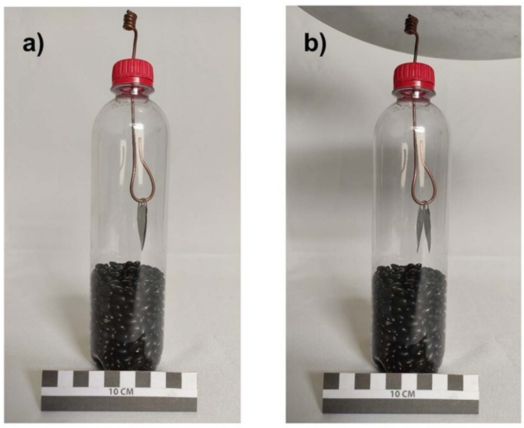

Figure 3. (a) Electroscope not working. (b) Electroscope working.

The electrophorus is an electrostatic generator that uses the previously mentioned electrification processes to accumulate a large amount of charges in a simple way, so that these charges can be reused several times to demonstrate effects involving the electric force.

The use of basic materials for demonstrating electrostatic phenomena, such as bladders and PVC pipes, proves to be ineffective in some situations due to the numerous variables that can interfere with their use.

The materials used in this experiment consist of (figure 5): circular Aluminium baking sheet (350 mm diameter); PVC pipe (25 mm of diameter and 100–200 mm of length); Epoxy glue or hot glue; PVC sheet; Wool sweater;

The experiment montage consists of the following steps:

Step 1: Perform a conductivity test on the circular aluminium baking sheet for pizza using a multimeter.

Step 2: Cut a piece of PVC pipe that will serve as a handle, big enough so that the handler does not touch the aluminium part. Any handle can be used, as long as the material is insulating.

Step 3: Glue the handle in the centre of the circular aluminium baking sheet for pizza.

It can be glued with epoxy glue or hot glue to ensure that it is well fixed.

Step 4: To generate a charge, lay a PVC sheet on a table, which should be larger than the electrophorus, rub the PVC with a woolen blouse, always following the same direction.

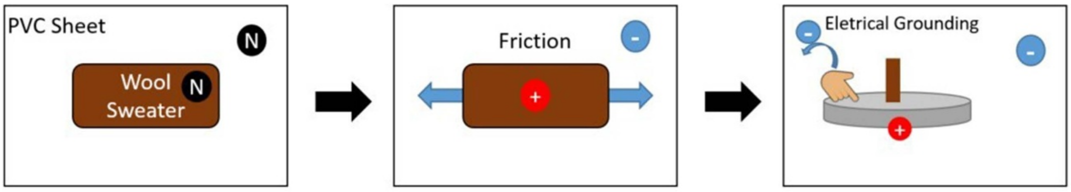

Figure 4. Schematic of the charging process of the electrophorus.

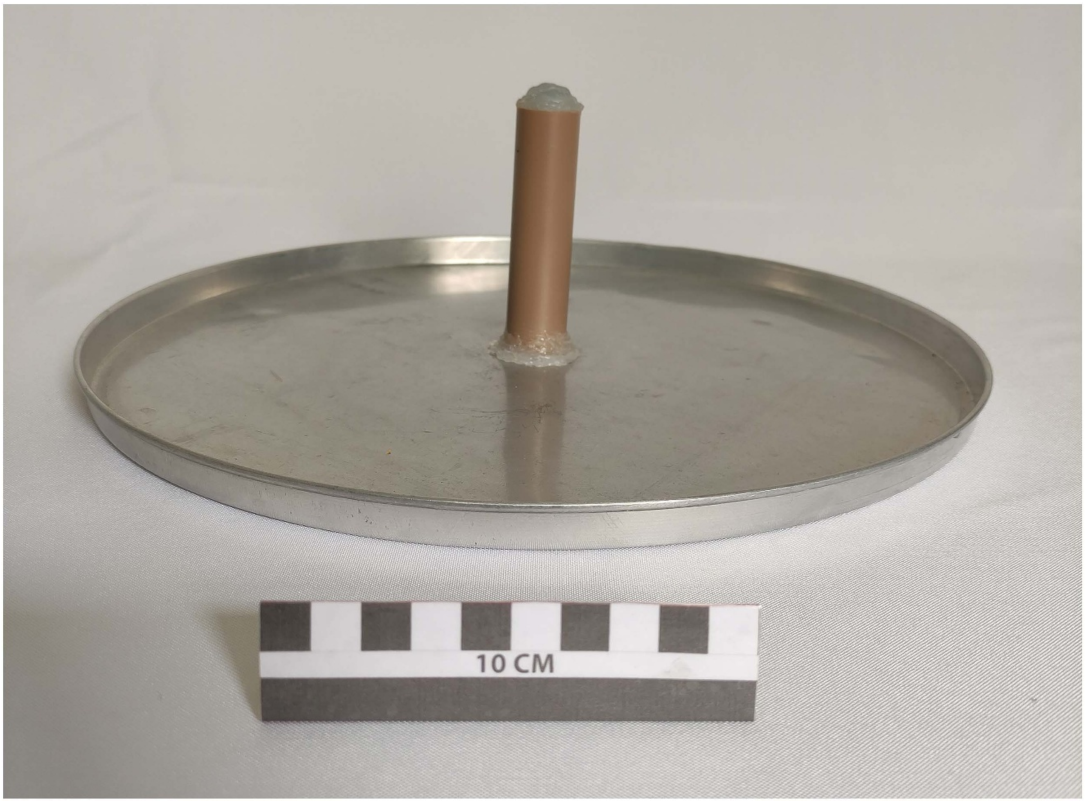

Figure 5. Electrophorus.

Place the electrophorus on the PVC sheet and then touch the metal part with your finger. Hold the cable, do not touch the metal part to avoid discharge and remove it. This way the generator will be charged.

2.3. Leyden jar

The Leyden jar was the first capacitor model created for studying the electrical properties of materials. Being a device with relatively simple assembly, it is widely publicized on the internet as a suggestion for students and teachers in the most diverse contexts of application, such as classes or science fairs. The Leyden jar consists of a bottle made of insulating material, filled with a conductive liquid. Two metal plates are attached to the bottle: one inside the bottle connected to a conductive material, such as copper wire, and the other to the outer plate. After charging the bottle, using a source of static electricity, electrical charges are stored in the internal metallic plate, being possible to generate small sparks when simultaneously connecting

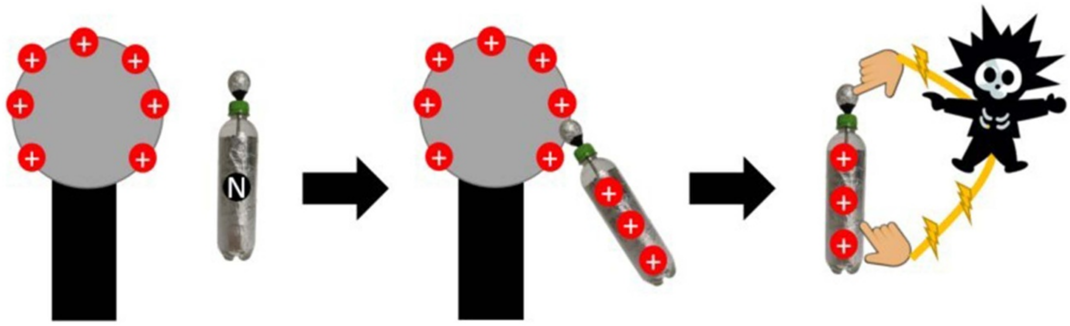

Figure 6. Leyden jar working diagram.

the internal and external plate (as displayed in figure 6).

The capacitance of the Leyden jar [22] depends on some factors related to its manufacture. The first factor to be analysed is the size of the bottle, since capacitance is directly proportional to the surface area of the bottle that is coated with conductive material. Thus, a bottle that has a larger coated area will have a proportionally greater capacitance, as it is in this region where the electrical charges will be stored.

In a complementary way [14], the standard format for commercially available bottles is cylindrical and, in this sense, a cylindrical capacitor was considered to perform the capacitance calculation. For a cylindrical capacitor, two cylinders separated by a distance d, charged with charges of opposite sign, are considered. Using equation (1):

$$C = 2\pi\epsilon 0 \frac{L}{\ln(a/b)} \tag{1}$$

where

L…. the length of the cylinders,

a…. the radius of the inner cylinder, and

b…. the radius of the outer cylinder.

Equation (6) demonstrates that capacitance, in addition to depending on the length of the bottle, also depends on the separation between the cylinders.

It is important to remember that this equation takes into account an ideal situation, and may undergo some modifications to describe real behaviours. In the case of the Leyden jar, the material that separates the cylinders has an electrical permittivity different from the value presented by the vacuum ($\epsilon_0 = 8{,}85.10^{-12}$ F m^{-1}), a factor that influences the capacitance value obtained. Thus, it is necessary to adjust equation (6), replacing the value of ϵ_0 by the value of the permittivity ϵ of the dielectric material used in the separation. The most common materials in the manufacture of such equipment are polyethylene terephthalate and glass.

The materials used in this experiment consist of: plastic or glass bottle; roll-on deodorant ball; aluminium foil; wire; hot glue or epoxy glue; water with salt;

The experiment montage consists of the following steps:

Step 1: preparation of the container that will serve as a structure for the experiment. Initially, it is necessary to coat the outer walls of the bottle using a sheet of aluminium foil. At this step, it is interesting that the coating is smooth, avoiding roughness that can interfere with the load storage process. The coating should not cover the entire bottle, leaving a distance of approximately 4 cm from both ends.

Step 2: making a hole in the bottle cap, so that the wire can pass through it. At one end of the wire, fix the deodorant ball with the help of hot glue or epoxy. After that, the ball is coated with aluminium foil, taking care to let the wire in contact with the aluminium foil by twisting it. Adjusting this structure to the bottle cap, a small sealing process is performed using hot glue.

Step 3: Finally, the bottle is filled with the salt water solution and closed, using the cap with the ball. Inside, the wire immersed in the solution will serve as a conductor for the charges that are stored in the metal sheet. It is observed that salt water in

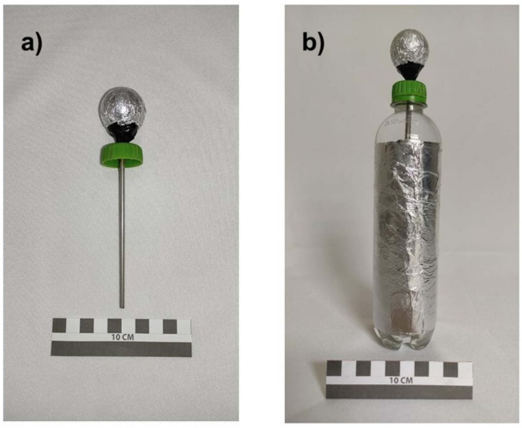

Figure 7. (a) Ball with wire fixed to the bottle cap. (b) Finished Leyden jar.

contact with metals causes an acceleration in the oxidation process, so it is necessary to carry out periodic maintenance in the experiment, in order to guarantee its long-term operation (figure 7).

2.4. Van de Graaff generator

As presented by Furfari [23], in his study entitled 'A History of the Van de Graaff Generator', the Van de Graaff generator was initially conceived and built by the American physicist and engineer Robert Jemison Van de Graaff in 1931.

Considering that it is an electrostatic machine capable of producing very high voltages in a reasonably simple way, it was mainly used in the area of nuclear physics to assist in studies involving the acceleration of particles. The models for these studies are usually large, with heights of around 13 m and metallic spheres with a diameter of 4.5 m. The educational models present in teaching laboratories are much smaller in size, with heights in the decimetre range.

The materials used in this experiment consist of: a wooden structural support, motor, support column made of insulating material, two rollers, two brushes of conductive material, a belt of insulating material and a metallic dome.

The operation takes place by the movement of the belt under the rollers, which are electrified with charges of opposite signs due to the friction between different materials, according to the principles present in the order found in the triboelectric series. At the top, the nylon belt is positively charged due to friction with the teflon-coated roller, which is negatively charged, as shown in figure 8. At that moment, electrons present in the metallic dome, initially neutral, flow through a conductive wire connected to a brush in order to neutralize the positive charge of the belt, thus charging the dome with a charge of the same sign. At the bottom there is another brush, electrically grounded, with the purpose of grounding residual charges present on the belt.

During the functioning of the Van de Graaff generator, three different processes of electrification are present [1]: electrification by friction, electrification by contact and electrification by induction (figure 8).

In electrification by friction, two materials that are initially neutral and of different compositions are rubbed against each other, causing a transfer of electrons between the bodies. This phenomenon can be described by the existence of atoms that are more likely to lose electrons while others are more likely to gain them through chemical bonds. With the purpose of helping in the choice of materials to be rubbed together to produce static electricity, a table was constructed, which became known as the triboelectric series, responsible for showing the tendency of the material to receive or donate electrons during the process.

In contact electrification, it is initially necessary that one of the materials is electrically charged while the other is neutral. When establishing a physical contact between them, the transfer of electrons between the bodies occurs until a state of electrostatic equilibrium is reached, where the ordered movement of charges is interrupted. This type of electrification appears in the Van de Graaff generator, for example, when it touches its charged dome.

In electrification by induction, an initially charged body (inductor) is brought close to a neutral body (induced). Due to electrical induction, the neutral body will present a separation of charges that will tend to neutralize the charge of the charged body. If the body is positively charged, this will induce a separation of charges in the neutral body, causing charges of opposite sign to be close to the charged body. Meanwhile,

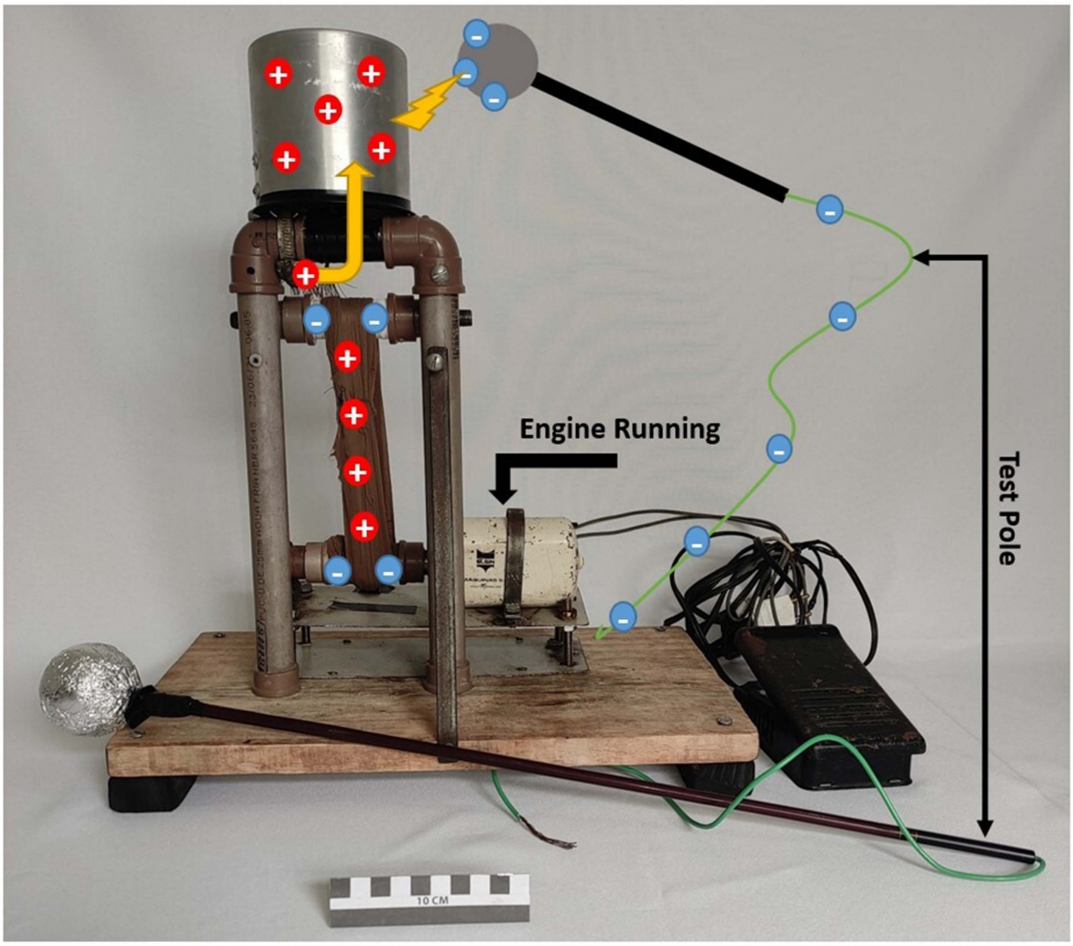

Figure 8. Van der Graaf generator.

charges of the same sign are repelled and, in the presence of an electrical ground, will result in charging the induced body with charges of opposite sign to that of the inductor.

According to equations and concepts found in the literature, such as in Leite [9], Moçambite [24] and Assad [25], it is possible to estimate the theoretical value of the maximum electrical charge accumulated in the metallic dome of the generator. Considering that the conductor in electrostatic equilibrium has a uniform distribution of charges, the maximum charge contained on its surface is given by:

$$Q = A \cdot \delta \qquad (2)$$

where A is the area of the conducting dome and δ is the surface charge density. Considering a point immediately outside the conductor, but sufficiently close to its surface, the value of the electric field can be determined as:

$$E = \frac{\delta}{\epsilon 0}. \qquad (3)$$

Adopting E as the value of the maximum electric field present in a region close to the surface of the conductor and ϵ_0 being the value of the electrical permittivity of the vacuum, tabulated as $\epsilon_0 = 8{,}85.10^{-12}$ F m^{-1}.

According to the literature, air behaves like an insulator when subjected to electric fields lower

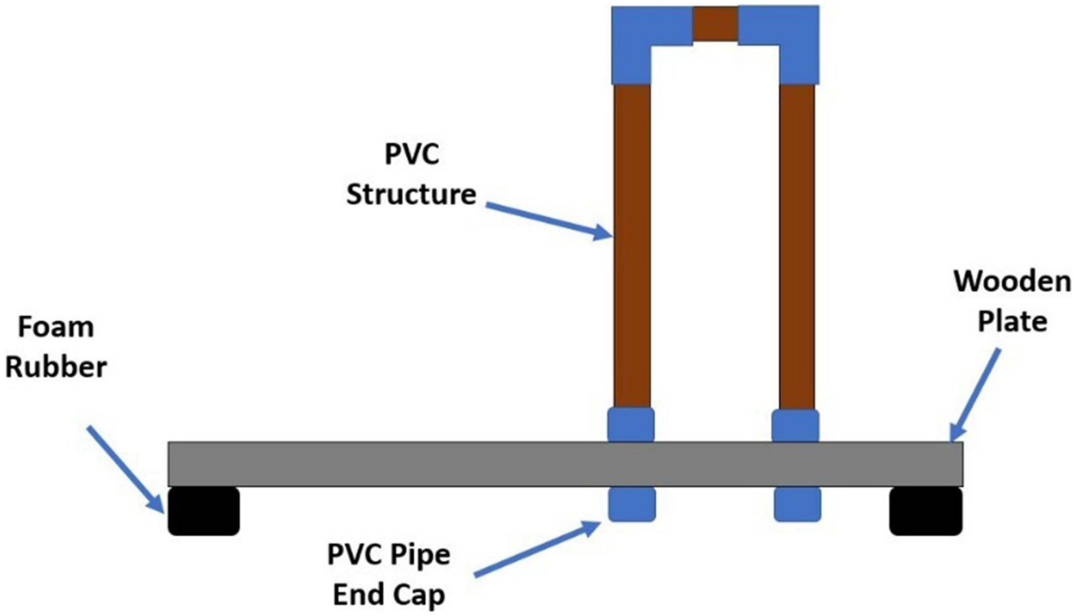

Figure 9. Assembly scheme of the PVC structure on the wooden plate.

than 3.10^6 N C^{-1}. Therefore, by approximation, the value of $E_{\text{max}} = 3.10^6\,\text{N C}^{-1}$ can be characterized as the maximum intensity of an electric field to which the air can be subjected before it becomes conductive (also described as the dielectric strength of the air).

To determine the numerical value of δ, it is necessary to observe the following relationship present in equation (4):

$$\eth = E_{\text{max}} \cdot \varepsilon_0 \tag{4}$$

Combining equations (2) and (4), we obtain:

$$Q_{\text{max}} = A \cdot E_{\text{max}} \cdot \varepsilon_0. \tag{5}$$

It is also possible to estimate the approximate value of the electrical potential present in the generator by analysing the distance between the conductive dome and a test rod at the moment when electrical sparks occur

$$V_{\text{exp}} = E_{\text{max}} \cdot d \tag{6}$$

where d is the average distance between the dome and the test rod at which sparks can be observed.

With regard to teaching, the use of the generator is shown to be a potentially significant activity for the students' understanding of general concepts of electricity such as static electricity, electrification processes and dielectric materials. The previous equations can be suggested by the teacher as a complementary activity to the students, so that they can work on the concepts in order to relate theory and practice when the subject is physics. As pointed out by Miranda [1], the use of experiments that facilitate the visualization and understanding of concepts, sometimes abstract in the students' understanding, acts as a very important tool in the teaching and learning process, especially in school environments. Therefore, one of the objectives of making this instrument was to indicate the possibility of using low-cost materials in the manufacture of a homemade Van de Graaff generator, since the conventional models available on the market have prices that vary between R$ 1000.00 at R$ 6900.00.

Step 1: consists of positioning the generator structure on the wooden plate that will serve as a support. With the aid of a ruler, two points were marked where the PVC pipes would be fixed, as shown in the diagram in figure 9. Then, the generator structure was assembled using PVC pipes: two 305 mm pipes, one 95 mm pipe coupled

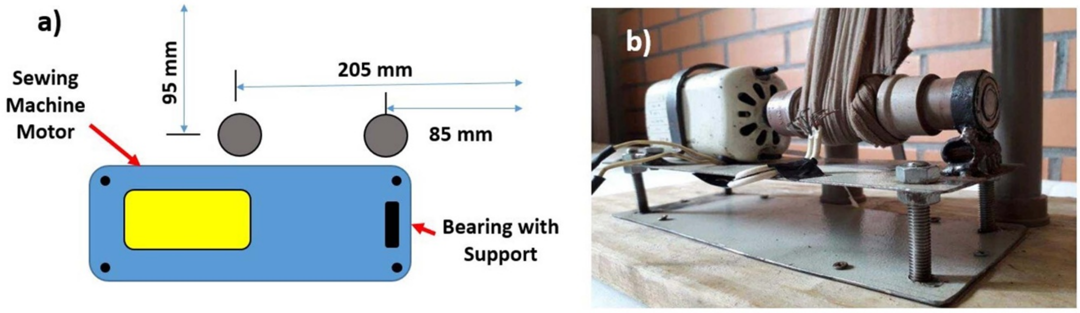

Figure 10. (a) Positioning scheme of the engine support. (b) Final arrangement of the engine support.

with the help of two 90 degree PVC corner elbows.

Step 2: Drill the wood plate at the previously marked points with the aid of a hole saw, fix the PVC frame on the base, putting two end caps on each of the lower ends of the tubes to better guarantee the generator's fixation. Two foam rubbers were also attached to the wooden plate with the help of screws, providing support and stability to the generator, as shown in figure 9.

Step 3: On the upper part of the PVC structure, two bearings were fixed with the help of cast iron plates and welded in the form of clamps, attached to the PVC pipes by means of rivets and two screws.

Step 4: At the bottom build a second structure using two metal sheets, to fix the engine that will make the generator work. Four screws were welded to the first plate at each of its ends. In the second plate, where the motor and a bearing coupled to a support were fixed, four holes were drilled coinciding with the position of the screws in the first plate.

Step 5: At the end, position one plate over the other with the help of the eight nuts, the structure was fixed to the wooden base using six screws. The purpose of this mobile structure is to help adjust the tension applied under the belt, ensuring that it can rotate without major disturbances. The positioning of the frame is illustrated in figure 10.

Step 6: To build the two rollers that would run with the belt, two 95 mm long PVC pipes were used with connectors at both ends. In this way, the roller will have a central space for the belt to work without getting out of alignment. In the upper roller, covered with teflon tape, two wheel bolts were fixed inside to connect it to the bearings. The lower roller (also with the aid of a wheel bolt), had one of its ends fixed to the bearing and the other end was attached to the motor rotation axis. This roller was coated with nylon. A photo showing both the metallic support for the bearings and the assembly of a roller is illustrated in figure 11.

Step 7: The belt that is between both rollers was made using a soft nylon fabric, sewn in order to form a band that was sufficiently tensioned in the space between the rollers positioned on the structure. The choice of material was based on the triboelectric series, taking into account the ease and low cost of teflon tape and nylon.

Step 8: The metallic dome, responsible for ensuring the accumulation of electrical charges, was attached to the upper part of the PVC structure using a clamp, so that it was possible to attach a set of copper wires to its interior with the aid of insulating tape. The other end of these wires was shaped into a brush and placed at a distance of approximately 10 mm from the nylon strip. The spacing was done taking into account that direct contact with copper could damage the belt made of a less resistant material. At the bottom, a brush was also made with copper wires 10 mm away from the belt, now connected to the metal plate with insulating tape to ensure the grounding of residual charge.

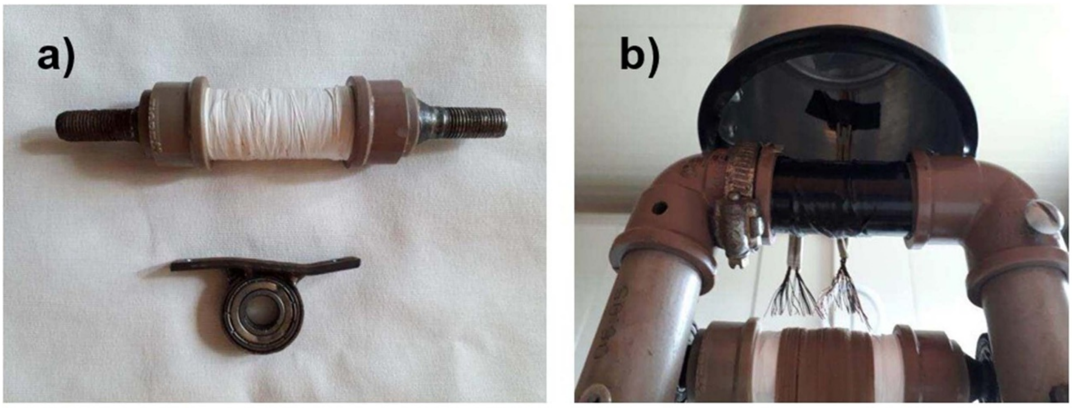

Figure 11. (a) Upper roller and bearing support. (b) Light wire attached to the inside of the generator's metallic dome.

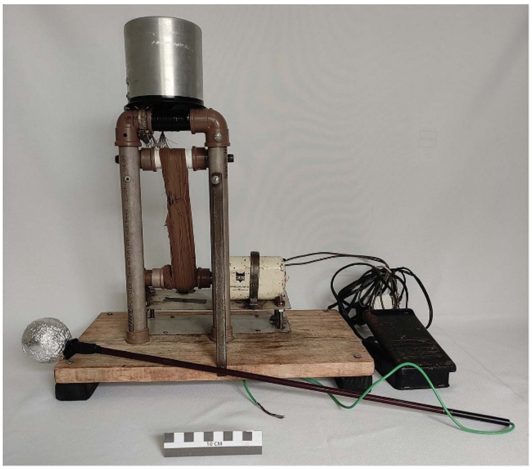

Figure 12. Finished generator assembly and test pole.

Step 9: The last element was the making of a test stick that provides a better analysis of effects such as sparking. It was necessary to envelop a sphere of approximately 8 cm in diameter in aluminium foil, ensuring that no part was left uncoated. A twist was also made in the aluminium foil at the base of the sphere in order to create a 'beak' in which a piece of copper wire was wound. Finally, the sphere was fixed to a tube of insulating material, which was used as a cable, with the remainder of the copper wire being grounded at the base of the generator. The final generator assembly and test pole are shown in figure 12.

3. Results and discussion

3.1. Electroscope

In this instrument, aluminium foil was initially used in a single strip folded in half. However, it had a restorative force that tended to keep the paper open in a 'v' shape. To solve this problem, this single strip was cut into two separate strips that were attached to the wire through a hole. After some improvements regarding the design of the two strips to the wire, we achieved a satisfactory result, where we could observe that the strips separated significantly whenever an electrically charged body was approached.

In the initial versions, the use of the bottle demonstrated that it did not have a stable balance even with small vibrations. In order to solve this problem, a weight was used at the bottom of the bottle, so that its centre of balance was lower and consequently increased its stability. After all the optimizations, it is observed that the climatic conditions, especially the relative humidity of the air, influenced the proper functioning of the device. Thus, it is suggested that on days when the relative humidity exceeds 60%, consider using a dehumidifier.

We emphasize that a satisfactory result was obtained when building an equipment completely made of reused material after all the modifications and improvements.

In order to use the electroscope in the classroom, it is necessary to develop a lesson plan, which takes into account appropriate teaching methodologies, with well-defined learning objectives, building a script that brings questions, which stimulate the student's critical thinking in relation to the subjects studied, considering the use of active methodologies.

3.2. Electrophore

In the tests carried out with the electrophore, it works according to the video [7]. However, some considerations are worth. In the tests carried out, a PVC sheet was used on which a wool blouse was rubbed to generate an electric charge. Note that the electrical charges accumulated at the bottom of the PVC sheet, and it is possible to use the generator to gather these charges. However, its use for charging electrical charges to other devices, such as the Leyden bottle, requires a large number of repetitions, exposing its low efficiency.

The problem seen with the accumulation of charges on the bottom of the PVC is considered to originate from a grounding process that is occurring due to the fact that the sheet used is very thin. To solve the problem, the best way is to use a thicker sheet, or use two layers of PVC separated by a layer of cardboard.

To avoid shocks when grounding electrical charges, you can use a coated copper wire, connecting one of its ends to the ground and the other end to the top of the circular aluminium baking sheet.

3.3. Leyden jar

In the tests, it was possible to note the versatility of the Leyden jar as well as the high capacity for accumulating electrical charges. This device can accumulate charges of around 10^3 Coulombs, capable of overcoming the dielectric strength of air and forming visible sparks with an average of 5 mm

It was observed that it is possible to build the bottle using aluminium foil on the inside. However, it is necessary to use a bottle that has a larger upper opening than the one used in this experiment, preferably with a lid, like the one used by Iberê in the video [8], and in this case the capacitance value of the bottle will be greater. For comparative measurements, we built two models: one using salt water and the other dry, with aluminium foil inside. When fully charged, the bottle with water produces a spark of about 7 mm, while the dry bottle produces a spark of about 12 mm. A problem noted when using the bottle is the relative humidity of the air, which on very humid days, the device discharges faster.

The Leyden jar can be used to carry out an experiment in class where the electric current passes through several people in sequence, which is very didactic to exemplify the functioning of the electric current [26].

We show that the construction of the Leyden jar is very simple and a fundamental part of any didactic laboratory that aims to study electrostatics. In this way, it is possible for the teacher to build the device together with the students in the classroom, applying different approaches to do so. It is crucial that all work to be done in the classroom is accompanied by good planning that uses a theoretical basis involving appropriate methodologies for the work that the teacher wants to do.

For better use of the equipment, we recommend that you use an electrostatic generator such as an electrophorus or a Van der Graaf generator to charge the bottle electrically.

3.4. Van de Graaf generator

In tests, the generation of static electricity was sufficient to demonstrate the effects of contact electrification and sparking. According to the theory, it was possible to calculate the maximum value of electrical charges accumulated at the top of the generator.

The area obtained from the dome, 0.034 m^2, was used to calculate the amount of maximum electric charge (Q_{max}). Considering the maximum value of the electric field (E_{max}) of 3.10^6 V m^{-1} present on the external face of the conductive material of the metallic dome and $\epsilon_0 = 8{,}85.10^{-12}$ C^2 N^{-1} m^{-2}, the value of Q_{max} found was $9{,}13.10^{-7}$ C or 0.9 μC.

For the estimated calculation of the electric potential, several measurements of the distances d between the test rod and the metallic dome were

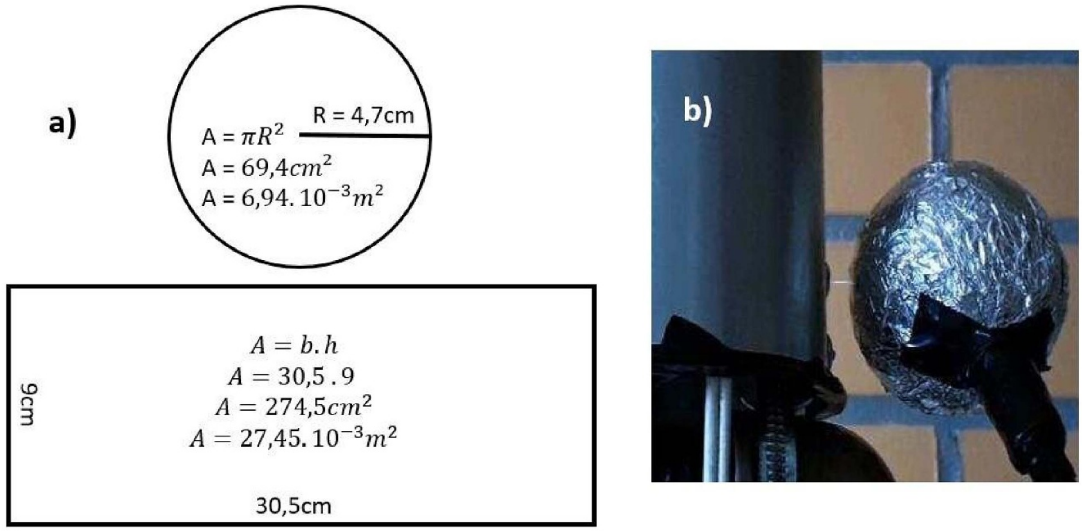

Figure 13. (a) Calculation of the surface areas of the dome. (b) Picture of an electrical discharge from the dome to the test pole.

carried out using a ruler. The average value of d found was 0.007 m.

The theoretical value obtained for the electric potential was 21.000 V. It is interesting to note that even if the voltage reaches very high values, it is possible to touch the generator without risking safety, due to the low amount of charge stored in the conductive dome.

Factors such as relative humidity, shape of the dome, imperfections and intrinsic characteristics of the materials used can cause the observed value to differ from the expected theoretical value. However, the use of equations and theoretical values, both for teaching purposes in the classroom and for an approximate estimate of the generator's operation, are shown to be valid tools.

The assembly presented in this study is efficient in generating static electricity. However, some small changes can be made in order to improve its performance. The metallic dome, for example, must have a very close to spherical shape (figure 13), thus reducing the pointed regions that tend to make the electrified body lose more charges when compared to the flat regions. The motor used was obtained from a sewing machine accompanied by the speed regulator pedal.

Regarding the material of the rollers and the belt responsible for electrification by friction, it is always necessary to observe the relationships present in the triboelectric series. Teflon has the greatest tendency to receive electrons of all materials, leaving it up to the developer to choose the material far enough from Teflon in the series to ensure better electrification. The option chosen in this work for this assembly was nylon. Finally, the list of costs present in the construction of this generator accounted for the approximate value of R$ 223.00.

From a teaching perspective, the generator presents itself as a possible alternative for teachers, when they intend to work on concepts related to electricity, facilitating the understanding of the concepts studied by the students and providing the creation of an environment susceptible to the exchange of ideas. The teacher can address, for example, physical concepts about electric conduction, electric discharges, static electricity, dielectrics. The generator can also be used as an auxiliary tool in other experiments.

4. Conclusion

This study allowed us to conclude, through the proposed instruments: Electroscope, Electrophore, Leyden jar and Van de Graaf Generator, that the elaboration of a laboratory for the study of electrostatics, applied to secondary education, proved to be viable, considering constructive aspects, costs and didactic implementation. In this way, the implementation of this project will provide students with a comprehensive and playful understanding of the physical phenomena studied.

Data availability statement

No new data were created or analysed in this study.

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