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Four physics jars

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Summary. — Experimental activities have a crucial role in physics education, because they represent one of the methods peculiar to discipline and facilitate the connection between experience and interpretation. They acquire particular significance if related and linked to every day experience. In this context we propose a reasoned sequence of experiences based on easy found and low-cost materials, suitable to shed light on essential concepts connected to a variety of physics fields. All illustrated four didactic proposals are carried out by using tinplate jars and each one drives at an integrated balancing between formal and informal education by scheduling various teaching methodologies in order to engage students having different learning styles.

PACS `01.40.Fk` – Research in physics education.
PACS `01.50.My` – Demonstration experiments and apparatus.

1. – Introduction

More and more physicists are addressing the problem of the student failure in understanding physics. Increasingly thorough and widespread research has shown that the majority of students has difficulty to learn essential physical concepts in the best of our traditional courses where students read textbooks, solve textbook problems, listen to well-prepared lectures, and do traditional laboratory activities [1]. Education research in physics has shown that learning environments that engage students and allow them to take an active part in their learning process can lead to large conceptual gains compared to traditional instruction [2-4]. Moreover, in the literature it has been shown that the direct learner involvement in building interpretative activities promotes formal thinking in the learning process [4]. An active learning environment is often difficult to achieve in lecture sessions, but low-tech and easy to do real experiments have proved to be really effective to create an active learning environment with successful results both in large and smaller high school classes and in classes for pre-service and in-service teachers. To this regard, we need to point out that informal and formal education necessitate for an accurate balancing and mutual integration, since many authors [5,6] have shown that the first approach mainly contributes to “knowledge *that*” while the latter to “knowledge *how* and *why*” phenomena occur. Indeed, suitable activities of careful considerations and reprocessing must be planned and wisely organized to allow the student to reach an adequate comprehension ensuring a correct knowledge placement in a frame of general laws.

Anyway, hands-on activities and small-group collaborative work have proved to be necessary (though not sufficient) powerful “interactive engagement” strategies able to address the prior misconceptions of students, modifying their incorrect ideas much more efficiently than the standard traditional physics course [7-9].

In fact, a direct, engaging and captivating exploration of natural phenomena is of crucial importance in student’s scientific education, leading them to perceive the scientific knowledge as a dynamic, socially constructed set of ideas. This set progresses through either evolutionary or even revolutionary changes in perspective [10]. Moreover, it has been found that secondary students who viewed science as a dynamic process of developing and changing ideas, and also considered interpretation and integration of ideas as strategies that facilitate learning, were more likely to understand scientific basic concepts, rules, laws and principles [10, 11].

The direct experimentation, combined with a self-made set-up useful for the same experiment, allows the student to improve both his problem solving skills and his deeper comprehension of involved phenomena [12-14], though the time required to accomplish the whole activity can be longer if compared with that needed in traditional teaching methods. On the other hand, many empirical evidences support the hypothesis that a personal interpretation of a process facilitates physics understanding and that this issue is facilitated and supported by a knowledge construction conceived as a complex-evolving process and by a learning method accepted as a time-consuming practice without shortcuts [15, 16]. More specifically, systematic research has demonstrated repeatedly that students who base their training on simple-certain knowledge and on quick learning are less likely to improve their physics knowledge and express essentially the same incorrect ideas at the end of an introductory university physics course as at the beginning [7-9].

Furthermore, science is about nature and learning science requires making connections with nature through practical activities [17, 18], even if usual teaching methods has been demonstrated to lack connection between subject concepts and every day world experiences [14]. Nevertheless, physics, as a widely spread opinion, is the most difficult and boring school subject in spite of its many every-day uses and its spread technological applications.

In this context, the role of the practical activity in physics education is seen as a vital one to provide a contextualized experience for the pupil so that he appreciates the physical world in which he lives and develops the skills by which a physicist conducts his investigations [19]. On the other hand, many of the groundbreaking historical experiments, though carried out employing commonly found materials, were characterized by detailed and deep analysis and thoughtfulness. Therefore reconstruction of these experiments can sometimes provide greater clarity than a modern systematic treatment, since the problems encountered with the original experiment can be compared with the student’s own difficulties in understanding [20]. With these views, we have designed a series of experiments (with easy found and low-cost materials) using also reconstructed devices of historical interest in order to achieve an in depth understanding of underlying physical phenomena. An experimental practice, scheduling activities of manifold typologies (ranging from the needed device implementation to measurement performance, result discussion and its placement in the correct frame of physical laws) has no alternative but to involve various teaching methodologies (each of which must be appropriate to the context). This approach can guarantee the engagement of all students, keeping them active in spite of the wide differences in preferred learning style, typically existing in a single classroom [21, 22]. Experimental activities based on low-cost materials are recommended also in educational institution where laboratories are well supplied with advanced equipments, because self-made devices allow the student both to understand the general working operation and to appreciate improvements enabled by modern technologies.

In this work we chose a learning approach based on the purpose of showing how common materials easily available at home can be employed in various and versatile ways to build interesting experimental set-up suitable for investigation in a variety of physics fields. Furthermore the learner can also achieve real numerical data ready for quantitative analysis.

2. – Energy from wind

For several years the energy issues are particularly present either in the scientific research or in popular general debate. In fact, the well-known planetary energy crisis enhances the need for energy alternative forms. Among these, a particular role is played by wind power, where the kinetic energy of wind is converted into electricity through a wind-powered generator. The first activity presented in this work is specifically addressed to show how a clean and renewable energy form (as the eolic one) can be readily converted into electric energy by means of relatively simple mechanical devices.

Historically, the oldest devices constructed to exploit the wind energy are a rudimentary kind of vertical axis turbines, used in ancient Persian mills.

The Savonius wind turbine is one of the easier devices, also called "*S turbine*", invented by the Finnish engineer Sigurd J. Savonius in 1922 and patented in 1929. This turbine, characterized by low environmental impact and noisiness, can be easily integrated into buildings without damaging aesthetics, as opposed to a windmill.

The construction of this simple kind of a wind turbine, allowing the lighting of a LED, enables an effective explanation of many didactical issues, especially those related to the conceptual node of electromagnetic induction [23, 24]. In particular it aims at illustrating that the induction is related to the motion of the inductor relatively to the circuit where the inducted current appears [25].

2˙1. *Experimental set-up*. – The set-up is composed by easy found and low-cost materials (fig. 1):

– 1 knitting needle

– 1 Pringles container

– 3 crown caps

– 3 rolls patch

– 6 GEOMAG

– 1 CD container

– 1 hairdryer

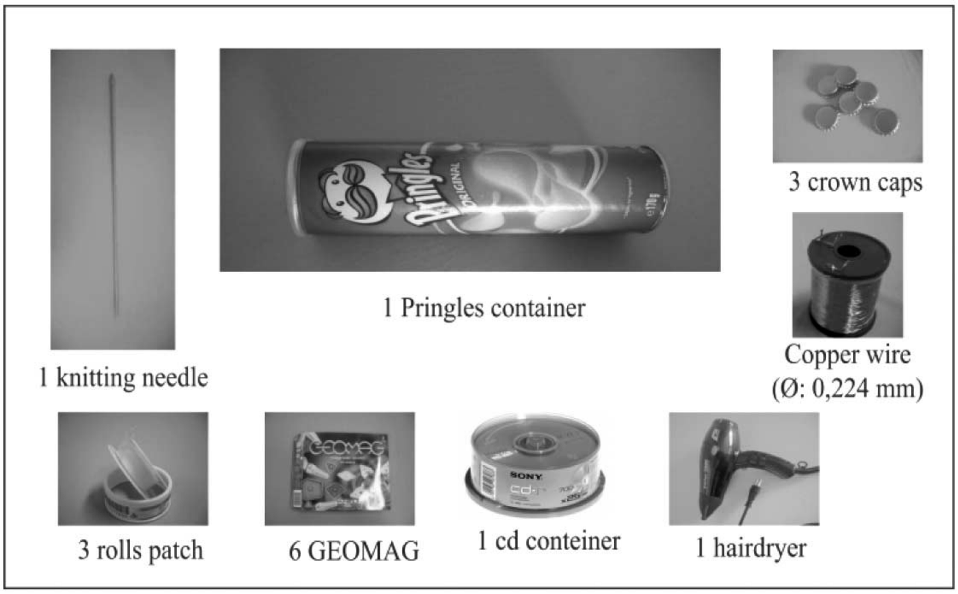


Fig. 1. – Materials employed.

First of all a primary wooden structure was built and the lower part of a CD container was fixed on it (fig. 2a). The two bushings for axis rotation were provided one from protuberance of the CD container and the other from a hole made on the upper part of the wooden structure (fig. 2b).

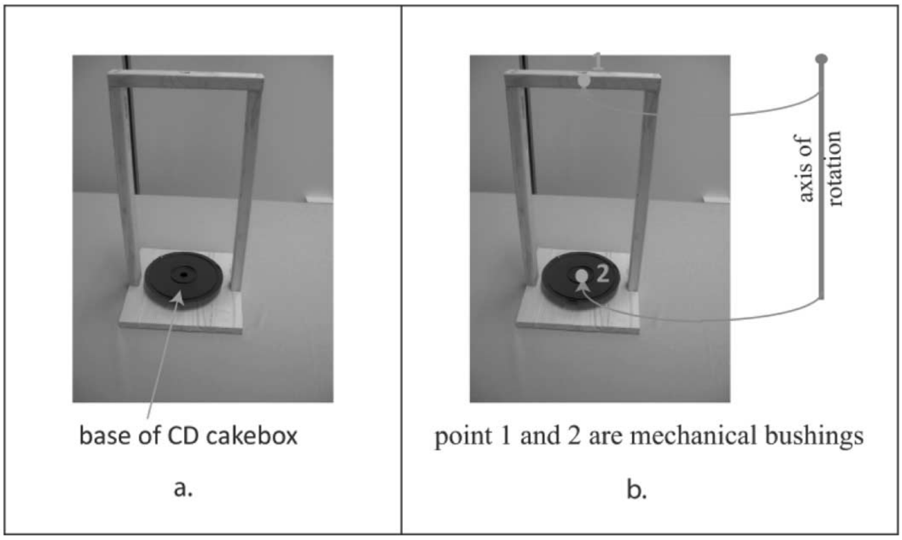
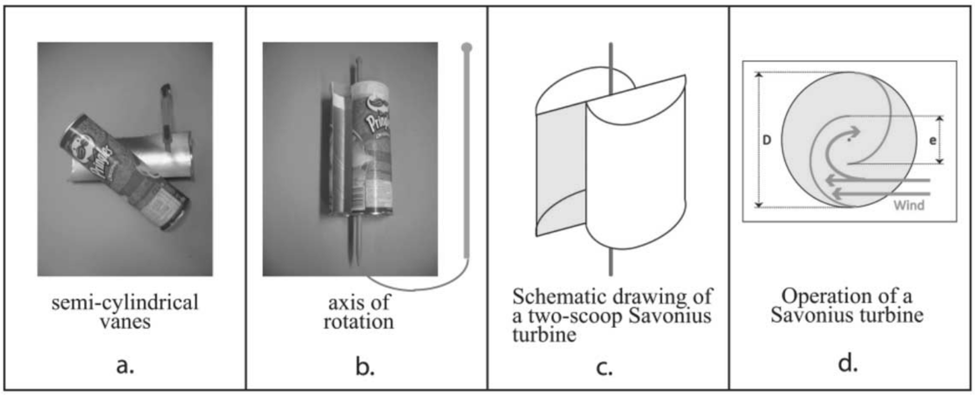


Fig. 2. – Retaining structure.



semi-cylindrical vanes
a.

axis of rotation
b.

Schematic drawing of a two-scoop Savonius turbine
c.

Operation of a Savonius turbine
d.

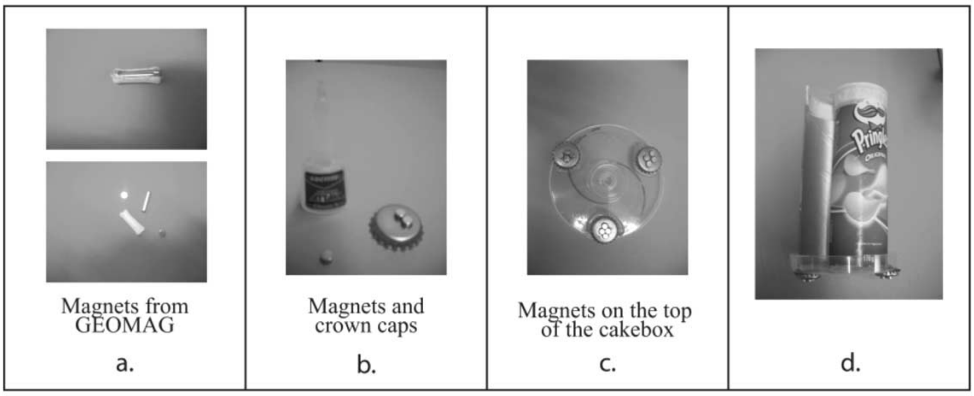
Fig. 3. – Turbine vanes.

In a construction second step, generator's vanes were built using a chips container (made of pressed cardboard), cut by a guillotine along its vertical section (fig. 3a).

The two so obtained semi-cylindrical vanes were fixed around the axis (represented by a knitting needle—fig. 3b), as described in the Savonius original model, for which the ratio between the vane extremes distance (e) and the imaginary cylinder diameter (D) (that contains the two vanes) is equal to 1/3 (fig. 3d).

The third construction step was dedicated to build magnets and coils, needed to convert kinetics energy into electric one. Magnets were built through common GEOMAG toy: 12 little magnets, obtained cutting geomags (fig. 4a), were attached (fig. 4b) by means of a quick-setting glue on three crown caps (four magnets with the same polarity on each cap). In this situation students may learn about magnet properties, particularly they can investigate the presence of two poles (north and south). The three just built magnets were fixed on the lower part of vanes by utilizing the cover of CD container (figs. 4c and 4d), so that they can roll above coils together the vanes.

Three coils were precisely created through rolls patch. Each coil is made of 200 turns, by using a copper wire with a diameter of 0.224 mm. These three coils were electrically



Magnets from GEOMAG
a.

Magnets and crown caps
b.

Magnets on the top of the cakebox
c.

d.

Fig. 4. – Magnet assembling.

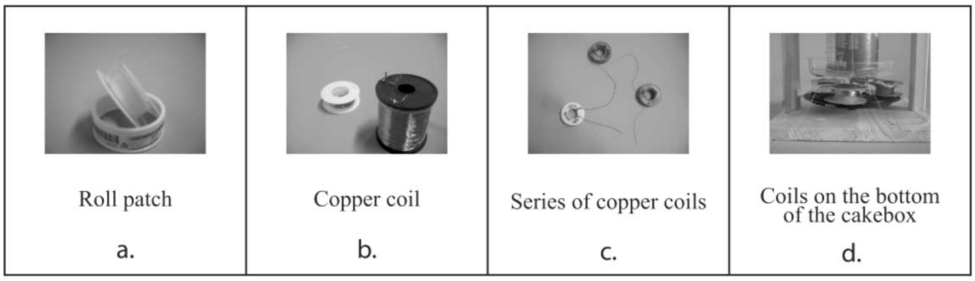


Fig. 5. – Coil construction.

connected in series and fixed on the lower part of CD container, previously attached on the wooden structure (fig. 5).

In the last step vanes were placed in the wooden structure and the three coils were electrically connected with a LED (fig. 6).

2·2. *Operation principles and learning outcomes*. – Many conceptual knots involved in the teaching process of learning about energy have been widely discussed in the literature [26-28].

Among these, the main ones are those which deal with energy as a state property, those which introduce energy conservation [29-32] and those which recognize the types

Fig. 6. – Finished turbine.

and transformations of energy involved in the various processes [26,33,34]. It is therefore important to offer systems which represent, as far as possible, those of existent plants for the generation-transformation of energy, in order to help understand that an energy source is nothing more than a transformation seat of energy in which a chain of types and transformations allows us, even with often modest output, to obtain the form of energy which can then be used for other industrial and domestic transformations. The realization, through the construction of one of these plants as in the case of the Savonius turbine, allows us to identify the seat of transformation and the types of energy involved: the kinetic energy of wind which hits the blades, the rotational kinetic energy of the blades, electromagnetic energy of the magnetic bobbin system when it interacts with the blades and the energy of the electrical current obtained as a result of the process. Furthermore the building of turbine, using easy found material offers the chance to explore in a subordinate and propaedeutic way, other phenomena like the interaction between magnets when trying to glue them together. Last but not least, the study of the way in which electrical current can be generated, starting from the rotating system, allows us to approach the different situations which illustrate the significance of the variation of a flow in electromagnetic induction, such as the variation in time of the field, of the surface area involved, of the orientation relative between them, which are, as we know, the object of another knot in the learning process that regards the electromagnetic phenomena [35-37].

Savonius wind turbine is an example of mechanical into electric energy transformation.

Our device utilizes the principle of electromagnetic induction, according to which an electric current can be produced in a closed circuit, placed in a magnetic field, when a magnetic flux concatenated with it changes in time. This phenomenon is described by *Faraday-Neumann-Lenz* law. Our circuit is made of three coils electrically connected in series between them and with a LED. Vanes rotation is obtained by a common hairdryer. The magnet motion, rotating above coils, induces an electromotive force creating the current for LED lighting. Peak-to-peak voltage, measured between the circuit terminals, is about 1 Volt.

3. – Kelvin electrostatic generator

In 1867 Lord Kelvin [38] presented to the Royal Society his studies on water-dropping collector for atmospheric electricity, and from his considerations the Kelvin electrostatic generator was born, a device which uses water trickle to generate a potential difference between two conductors.

Lord Kelvin stressed the didactic value of this tool to illustrate an important part of electricity:

> "I may take this opportunity of describing an application of it to illustrate a very important fundamental part of electric theory".

In this our work a simplified experimental apparatus is proposed to provide a useful tool addressing the crucial conceptual nodes in scientific learning related to electrostatic problems and charge processes.

3˙1. *Experimental set-up.*

– Low-cost materials (easy to found) were again used, to construct this tool (fig. 7):

- Two-liters steel container
- One-liter steel container

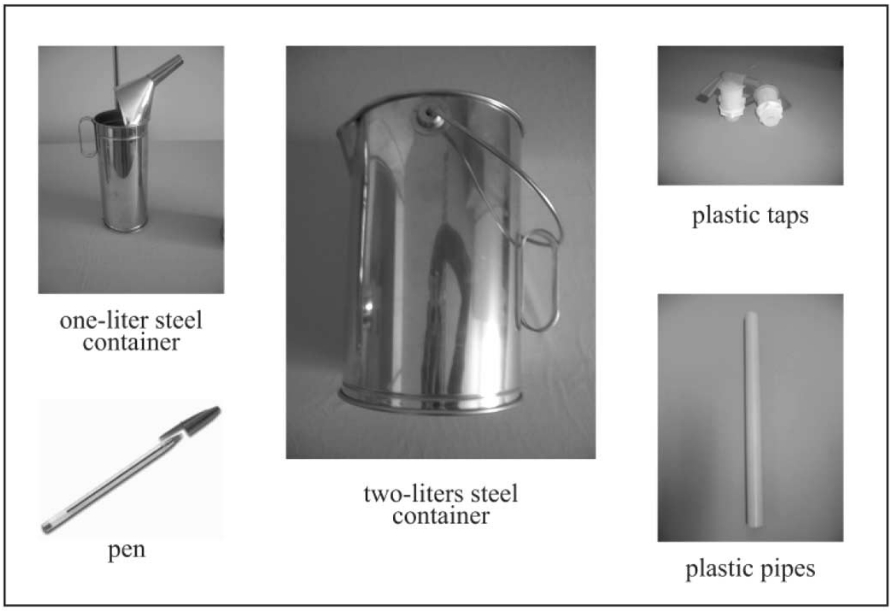


Fig. 7. – Materials employed to build the Kelvin generator.

- Plastic pen
- Plastic taps
- Plastic pipes

The containers and metal rings were electrically connected following a crossing scheme (A was connected with B′ and A′ with B—fig. 8), while, in order to ensure electrical insulation of all the metallic conductors among them and from ground, all the supports were made using plastic materials.

Side rings (fig. 9a) and containers base (fig. 9b) were obtained by cutting one liter steel vessels. A plastic support was fixed on each one, in order to allow their assembling on the retaining structure. Two plastic valves were placed on the steel container of two liters. All assembled elements were then fixed on a plastic pipe, ensuring the needed insulation.

3˙2. *Operation principles and learning outcomes*. – If one conductor is provided with an electrical charge (for example, a small negative charge is furnished to the container B′—fig. 10a), the ring A, electrically connected to it, takes a charge of the same sign (fig. 10b). In turns, ring A (negatively charged) polarizes water dropping by R_A tap (fig. 10b), so that when drop detaches and falls, it brings a small quantity of charge of opposite sign (positive in this example), transfers it to the container A′ (fig. 10c) and leaves on the top container C an equal but negative charge. The same process simultaneously occurs, with inverted charges, along the crossed branch starting at R_B tap, so that the C container remains nearly neutral. The water continuous dropping produces an increasing cumulative charge separation, for which the necessary energy

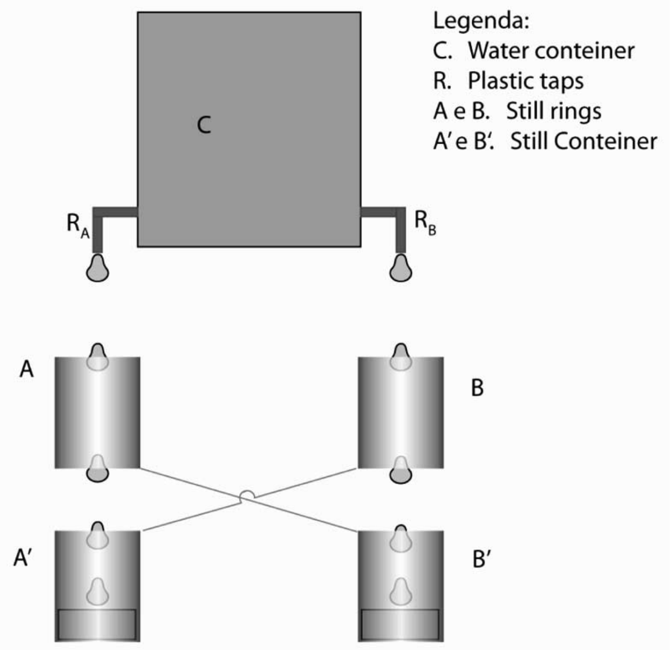


Fig. 8. – Scheme of the electrostatic Kelvin generator.

is provided by gravitational field. Charge accumulation can be highlighted by placing aluminum leaves both on A and B and observing their increasing divergence.

When the so created potential difference between A and B increases enough to overcome the value of dielectric strength between two sharpened conductors connected to A and B, a spark will go off and the process will restart as previously described.

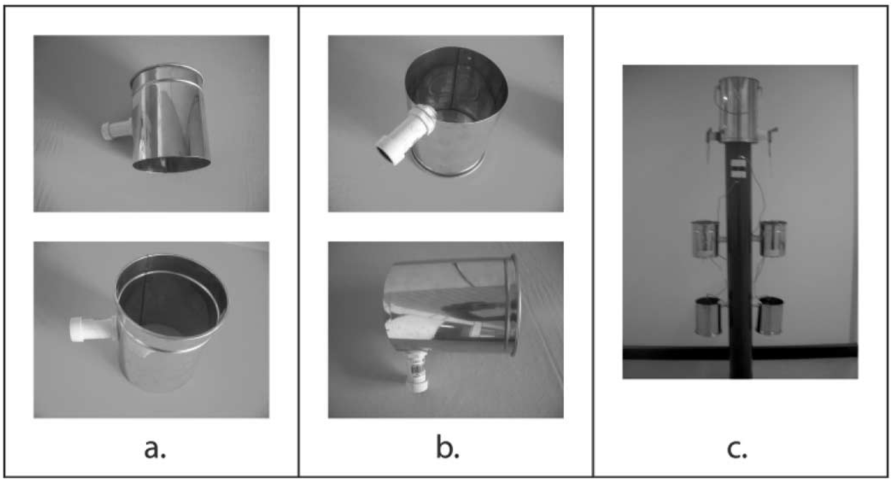


Fig. 9. – Details of some components of the Kelvin generator.

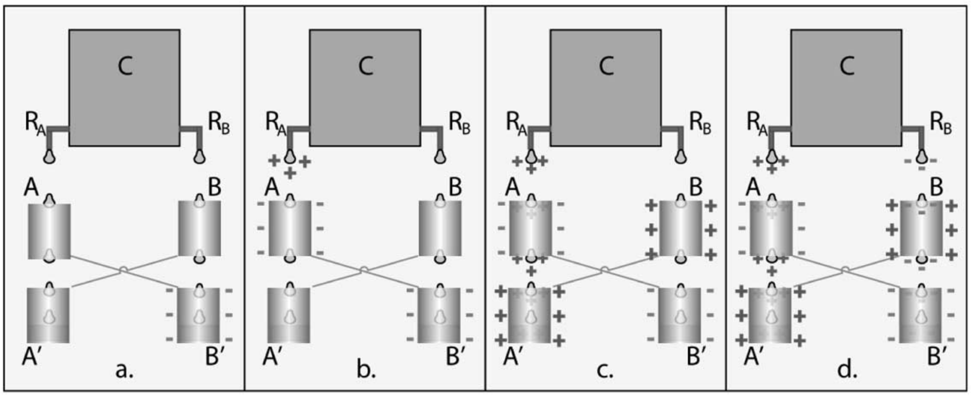


Fig. 10. – Operation of the Kelvin generator.

The analysis and discussion of this experiment allows the teachers to address important conceptual knots [39-44], for example electrization processes as charge separation, the different ways in which an object can be charged (by rubbing, contact and induction), the Faraday cage, the mobility of the charges in the conductors and the situation of equilibrium between the electrically connected containers, the conductive properties of water highlighted by the fact the water in the upper container remains electrically neutral and the conservation of the charge which can be analyzed in the whole system. The apparatus can be analyzed also from an energetic point of view to recognize that the necessary amount of energy must be provided by an external field, just as the gravitational one is in this example.

4. – Volta's condenser electrometer

Condenser electrometer is a tool designed by A. Volta (1745-1827) to detect tiny potential differences otherwise not appreciable.

This proposed simple apparatus, as the previous, again addresses the conceptual node of charge separation processes, but this time the muscular work of the experimenter supplies the necessary energy. Furthermore, the concepts of capacity and of capacitor can be efficiently highlighted.

4˙1. *Experimental set-up.* – Used materials are low cost and very easy to find (fig. 11):

- 1 glass jar
- 2 metallic lids
- 1 plastic pen
- 1 plastic piper
- 1 plexiglass sheet

In a first step the detector was built using two parallel strips of thin flexible aluminum leaf, electrically connected with a jar lid that will be the first capacitor armor (fig. 12a). The second armor was built by using another lid on which an insulating handle was fixed (fig. 12b). Figure 12c shows our Volta's condenser electrometer.

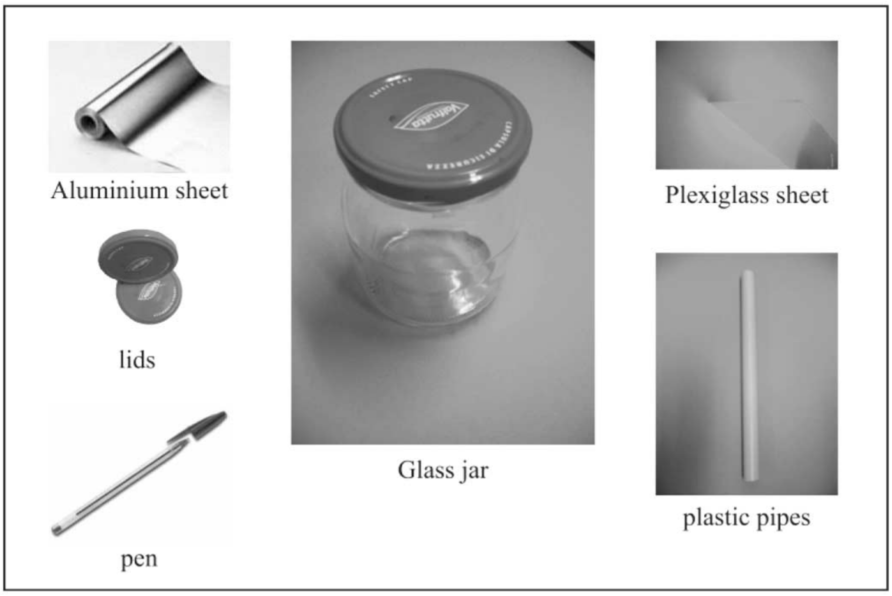


Fig. 11. – Materials employed to build the Volta electrometer.

4˙2. *Operation principles and learning outcomes.* – Bottom lid, electrically connected with the leaves, is charged through a plastic pen previously electrified by rubbing. This operation does not produce any visible effect on leave separation because of the little transferred charge. The lid is then grounded, and the experience is repeated placing on the lower armor the second one holding it through the insulating plastic handle. The electric insulation between armors is supplied by interposing a thin plexiglass sheet. At this point the bottom armor is once again electrified by the plastic pen, while grounding the top armor. Successively, after removing ground connection, the experimenter lifts the top lid and can observe a significant separation of leaves.

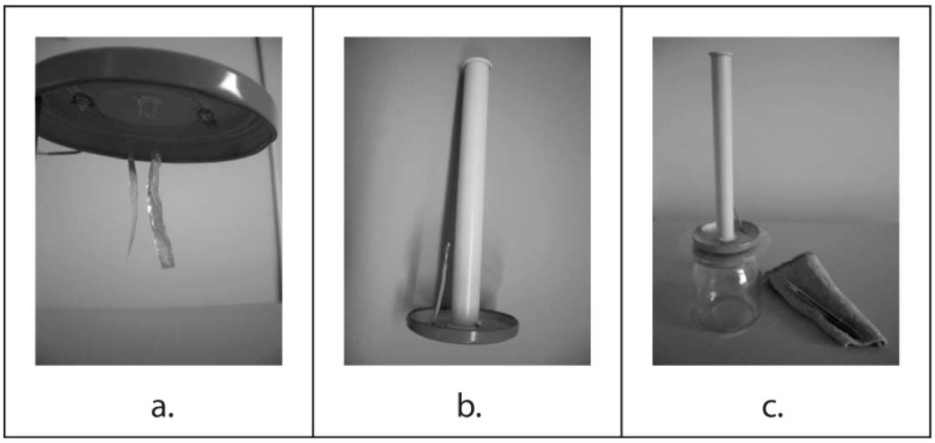


Fig. 12. – Details of some components of the Volta electrometer.

Fig. 13. – The stalagmometer.

The analysis and discussion of this experiment allows the teachers to shed light on this new charge separation process [39-45] clarifying differences with the Kelvin generator. In fact, in the present case the charge separation is obtained as a consequence of the capacity decreasing when the top armor is lifted up. This action causes an abrupt increasing of the potential of the leaves because of the charge conservation and falling capacity ($V = Q/C$). In order to remove the armors, since some force is required overcoming the electrostatic attraction between them, corresponding energy is provided by the experimenter muscular work, analogously to that carried out by the gravitational field in the previous case. The comparative deployment of the two proposed electrostatic devices allows students to see how the same energy-requiring process (charge separation) may be attained through the conversion of two quite different forms of energy: muscular and gravitational.

5. – Stalagmometer

The last proposed experiment concerns the construction of a stalagmometer, suitable for surface tension measurements, normally conducted in university teaching laboratories with more sophisticated instrument.

Experimental apparatus (fig. 13) is made of a wooden support on which a little pan (containing the fluid under investigation and supplied with a small tap) was fixed. A small jar is located on a precision balance (0.05 g sensitivity) under the pan to collect the falling drops.

Tate law (determined by the balance of forces acting on a droplet) is expressed as

$$Mg = 2\pi R\sigma,$$

where M is the drop mass, R the tap radius, σ the fluid surface tension and g the gravitation acceleration.

The simplest use of the apparatus needs its calibration with a fluid of known surface tension to avoid difficulties related to measurements of device geometrical parameters. Distilled water in standard condition ($\sigma_w = 72.7\,\mathrm{dyn/cm}$) can be used in the calibration procedure, in which 25 drops are weighted (to obtain the single drop mass $M_w = 0.026\,\mathrm{g}$) obtaining the device calibration factor from the relation

$$K = \frac{M_w g}{\sigma_w} = 3.6 \times 10^{-3}\,\mathrm{cm}.$$

If the pan is then filled with another fluid (for example acetone), the experience can be repeated measuring the mass of a number of drops sufficiently high to limit experimental error (typically 40 drops).

The so obtained acetone surface tension results:

$$\sigma_{\mathrm{acetone}} = 27.8\,\mathrm{dyn/cm}$$

with a relative error of 0.2.

The activity described (though realized with very low cost materials) permits us to measure the surface tension, a physical quantity usually difficult to estimate in high school laboratories. In addition, the proposed experimental activity allows learners to become familiar with the idea of the "calibration procedure of an apparatus" and to come to terms with some of the problems normally connected with data acquisition and processing.

6. – Conclusions

In this work we have presented a series of suggested experiments to be realized with homemade apparatuses built by easily found and low-cost materials. These experiments deal with different arguments such as: energy conversion, electromagnetic induction, electrization processes and work in charge separation, cohesion forces and surface tension. Each "physics jar" allows students to gain insights into some conceptual knots concerning different aspects involved in the process of planning and the setting up of the apparatus. In this way, for example, the construction and operation of a wind-powered generator permits us to reflect on energy as a state property, energy conversion and conservation in a power generator through a catena of energy conversion, involving the analysis of magnetic interaction and the investigation of electromagnetic induction as a result of a variable flux of the magnetic field.

The two different electrostatic machines allow us to recognize how the processes of separation of the charge are the basis of the production of differences of significant potential and how such processes are of a different type and nature. The electrical properties of the systems in relation to materials highlight the property of conduction and capacity which are the basis of the principles of functioning of the machine itself but also of the understanding of the difficult relationships between charge capacity and potential. The latter constitutes learning knots which still today are among those most talked about in books with a request at the same time for an analysis on an operative level of the same sort that the home-made apparatus allows us to carry out in the project phase, thanks also to the structural and conceptual modularity which is brought about during their creation.

Finally, some of the fundamental ideas underlying the operation of a measuring device are introduced in the context of the surface tension determination. The manifold typologies of scheduled activities start from material finding, proceed through device setting up, go on with data collection and are completed by results discussion. Consequently various teaching methodologies must be involved, so that all students are engaged and kept active in spite of the wide differences in preferred learning styles which typically exist in a single classroom.

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