Low-cost electrostatic experiments

Leoš Dvořák
Department of Physics Education, Faculty of Mathematics and Physics, Charles University in Prague, V Holešovičkách 2, 180 00, Prague 2, Czech Republic.

E-mail: Leos.Dvorak@mff.cuni.cz

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Abstract
Modern materials, components etc. enable us to create new variants of electrostatic experiments and demonstrations. Such experiments – simple, cheap, transparent and often also surprising – proved to be quite interesting for both teachers and students. The paper presents a series of simple electrostatic experiments and instruments that can be built by teachers or students themselves and can be used in various ways: for demonstration of basic phenomena, active engagement of students, teaching and discussing basic concepts of electricity, inquiry-based teaching and learning etc. Some methodological issues of using of these experiments are also discussed. The experiments were successfully piloted and used both in pre- and in-service training of physics teachers in The Czech Republic.

Keywords: Low-cost experiments, Electrostatics, Teacher Training.

Resumen
Los modernos materiales, componentes, etc. Nos permite crear nuevas variantes de los experimentos de electrostática y experimentos. Tales experimentos – simple, barata, transparente y con frecuencia sorprendente también – resultó ser muy interesante para los profesores y estudiantes. El documento presenta una serie de sencillos experimentos de electrostática y los instrumentos que pueden ser construidos por los profesores o los propios estudiantes y se puede utilizar de varias maneras: Para la demostración de los fenómenos básicos, la participación activa de los estudiantes, la enseñanza y discusión de conceptos básicos de electricidad, basada en la investigación, la enseñanza y el aprendizaje, etc. Algunos aspectos metodológicos del uso de estos experimentos también se discuten. Los experimentos se ensayan con éxito y se utiliza tanto en la pre y la capacitación en servicio de los profesores de Física en la República Checa.

Palabras clave: Experimentos de bajo costo, Electrostática, Formación del Profesorado.

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I. INTRODUCTION

Electrostatic experiments are known for centuries. Yet, some modern materials, components, commonplace equipment or toys enable us to create new variants of these experiments and demonstrations. Such experiments may be simple, cheap and often surprising for pupils and students. (Some of them proved to be surprising even for physics teachers). Experiments of this kind attract students' interest and physics teachers can use them in many ways: for demonstration of basic phenomena, active engagement of students (from simple "playing with physics" in physics clubs for kids to projects for high-school students), for teaching and discussing basic concepts of electricity, inquiry-based teaching and learning etc.

Though electrostatic experiments are described in many textbooks from high-school to standard college and university course books, (*e.g.* [1, 2]) and in some textbooks also new experiments using *e.g.* plastic sticky tape are used extensively [3], it is always useful to try to develop new variants of low-cost experiments. Some of them can even involve simple quantitative measurements. Some examples of such experiments were presented by the author at GIREP-ICPE-MPTL conference in 2010, see [4].

This article will concentrate mainly on qualitative experiments, with just a few quantitative "extensions". In spite of their simplicity they can be used at various school levels since junior secondary (or even elementary) till introductory university level, at which they are particularly suitable for courses for future physics teachers. We have piloted and used these experiments in pre-service training of physics teachers at Faculty of Mathematics and Physics of Charles University in Prague. We used them also in both formal and informal in-service training of physics teachers in The Czech Republic obtaining and evaluating mostly informal feedback. The experiments including the methodology of their possible use will be also used in modules for teachers in courses and activities supporting IBSE teaching and learning in Europe in the framework of the project ESTABLISH (SIS-CT-2009-244749; "European Science and Technology in Action Building Links with Industry, Schools and Home"). They should support active engagement of students, enable to apply "inquiry based" approach to introductory part of electricity even at a rather elementary level and help to develop "physics intuition" of pupils and students including both conceptual understanding and some quantitative estimates of values of quantities like charge.

The experiments described below are not meant in any way as the "last word" in simple electrostatic experiments. Rather, they should provide an inspiration for physics teachers and educators, not only in countries where it is difficult to obtain more expensive instruments and lab equipment.

II. EXPERIMENTS TO START WITH

Most of our experiments will use very simple tools – common plastic straws. (Note: Most straws can be charged very easily but some very thick ones are less suitable, so it is necessary to check them before using in experiments).

Perhaps the simplest experiment to start with is to charge a straw by rubbing it by a piece of cloth or a paper napkin and to put it to a blackboard or to a wall. The straw sticks to the surface (se Fig. 1).

This may be considered as rather silly experiment appropriate just for small kids. But it is surprising that also older students and adult teachers are quite keen to try to which object or surface the straw sticks and how long it can stay there.

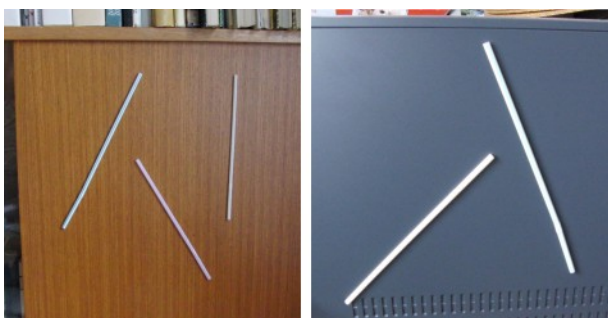

FIGURE 1. The charged straw sticks at various surfaces.

Here are some questions one can ask and try to answer either experimentally or theoretically:

- At what surfaces the charged straw holds?
- Does it hold on metallic surfaces, too?
- How long will it stay stuck to the surface?
- Will it hold at the ceiling? How large is the force between the straw and a surface?
- How intensively should one rub the straw to charge it?
- Why does a charged straw hold on a non-conductive surface? Why on a conductive one?

Of course, as in all electrostatic experiments, the experimental results depend on many circumstances. But many people are surprised that in good conditions the straw can stay attached even for days. Also, they often do not realize that it is not necessary to rub a straw many times to charge it – that, in fact, not rubbing but mutual contact is necessary.

Surely, this very first experiment basically shows just that "there is an interaction" (between charged object and other objects). To extend it, two charged straws are needed. They enable to perceive the interaction "at one's own hands" or rather fingers, see Fig. 2. To be fair, there is a small "mechanical trick" in this experiment. Straws act as levers so the force perceived by fingers is larger than the force of the repulsion itself. Still, to many people (even professional physicists) it is a bit surprising that the force can be clearly felt in such simple way.

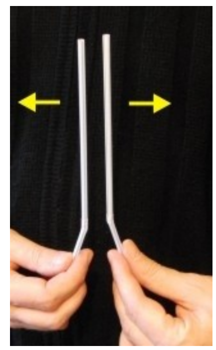

FIGURE 2. The repulsion of charged straws can be perceived by one's own fingers.

If we change the setup slightly and put one straw above the other as it is shown at Fig. 3 then the upper straw nearly "flows" above the other. (Our fingers should just prevent the upper straw from sliding to the side). The height at which the upper straw is floating can be several centimeters. If the lower straw is replaced by a larger charged plastic rod (some plastic draining pipes are ideal for this) then the height may be up to twenty centimeters.

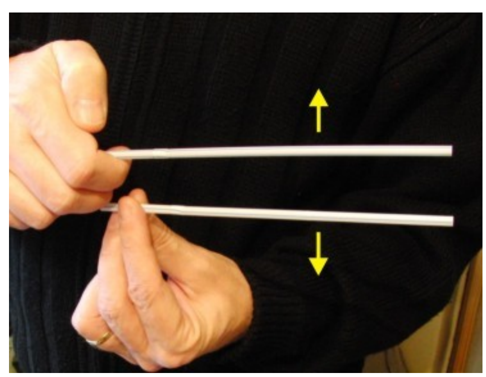

FIGURE 3. The electrostatic repulsion can balance the weight of the straw.

This simple experiment can be used also for rough estimation of the value of charge of the straw – see section V. below.

Both experiments with two straws mentioned above provide an opportunity to ask various specific questions, for example: What force do we perceive? How large is the force? Does the force depend on the distance of the straws? Or, in case students already have some physics background: Which physical law can be used to describe the repulsion?.

We can also use the experience gained from these experiments to build the concept of electric field.

III. SIMPLE INDICATORS OF ELECTRIC FIELD

Up to now we have not used any instruments in our experiments. The next step could be to build very simple instruments that can indicate the presence of electric field (or, if we do not like to speak about electric field, the presence of nearby charged object).

The simplest indicator can be just a piece of a straw hanging at a piece of thin thread. After the piece of a straw is rubbed it is repulsed from negatively charged objects and attracted to positively charged ones (*e.g.* a glass rod or glass test tube charged by rubbing), see Fig. 4.

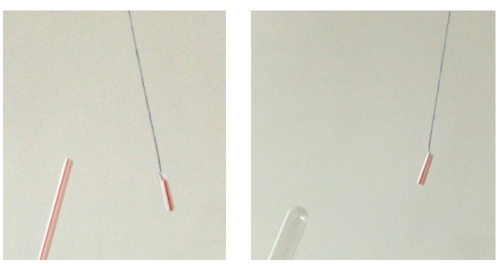

FIGURE 4. A piece of charged straw on a piece of thread as a very simple indicator.

Using a straw, paperclip and a piece of thin thread a simple "torsion balance" can be built, see Fig. 5. In this case, just one end of the straw should be charged.

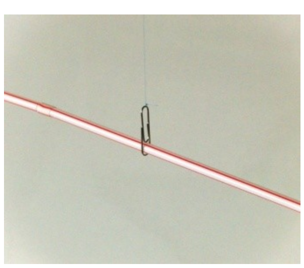

FIGURE 5. Simple "torsion balance" for indicating electric field.

A bit more "robust", reliable and sufficiently sensitive indicator uses a straw that can rotate along an axis consisting of a pin stuck into a thicker wooden skewer, see Fig. 6. The straw should be first pierced by a thicker pin; a small bead below the straw lowers the friction. Again just one end of the straw should be charged by rubbing. The other end can be marked; it will aim in the direction of electric field.

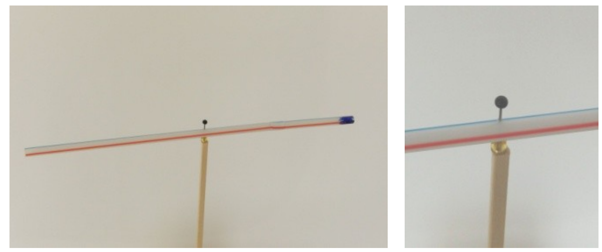

FIGURE 6. A more "sophisticated" indicator.

This indicator can be either held in a hand or the lower end of a skewer can be stuck into some suitable base, *e.g.* a piece of Styrofoam. The indicator can detect the field of a larger charged plastic rod at a distance of nearly one meter.

A variant of an indicator interesting perhaps rather for kids (in physics clubs etc.) is shown at Fig. 7. Now the straw is put on a "boat" from a plastic cup floating on water.

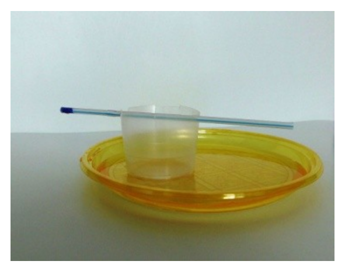

FIGURE 7. A variant of an indicator using a straw on a "boat".

Of course, all these indicators are suitable just for qualitative measurements. They can distinguish sign of the charge of various charged objects (plastic rods, glass tubes, sticky tapes put apart from some surface, plastic folders to which some paper was attached and then removed etc.). Note that the last experiment is good for reminding that, in fact, it is not rubbing the surface what is necessary for charging some object but the contact of surfaces and breaking of this contact). The experiments also clearly show that the force is greater in smaller distance from a charged object and can also indicate that the force is greater if the charge is greater – to show this we can put one charged straw at one side of the indicator's charged end and two straws at the other side, see Fig. 8.

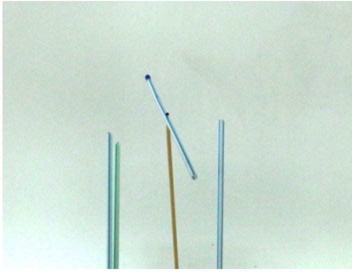

FIGURE 8. Balance of forces acting on a charged straw.

Note: Though it may be tempting to compare the distances and try to check whether they agree with Coulomb's law and the fact that the charge of two straws is two times greater than the charge of one straw, this procedure does not work very well. Not only the charges of the straws need not be exactly the same but they are also not point-like. So the experiment is really just qualitative.

To make it at least semi-quantitative, we can charge just the end of straws, turn the axis of our indicator to be horizontal and make one of straw's ends shorter. This enables to estimate, at least roughly, the value of repulsive force; but we will not describe this experiment here in greater details.

One point which is necessary to discuss when doing these experiments concerns the fact that the charged end of the straw is attracted also to conductive objects, for example to our hand because this may influence the experiments. Naturally, it may be the starting point of discussing charge distribution and electrostatic induction.

IV. HOW IT CAN BE PROVED THAT THE PLASTIC ROD IS REALLY NEGATIVELY CHARGED

The fact that a plastic rod or a straw is charged negatively after rubbing it by a cloth is written in textbooks. But how do we know it? Or, to be more precise, how can we prove it in a simple way? Or, to be even more precise (and less ambitious): How can we prove that the sign of a charged straw is the same as the charge at a negative terminal of an ordinary electric cell – and how to do it in a simple experiment transparent enough for pupils and students?
An indicator with the circuit diagram at Fig. 9 can help.

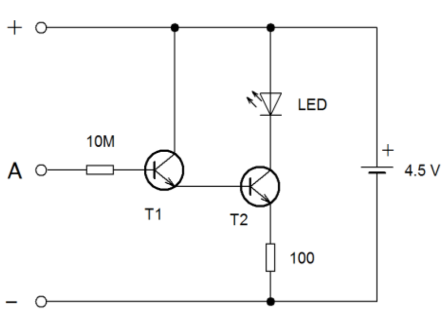

FIGURE 9. An indicator with bipolar transistors.

The indicator uses common bipolar transistor, for example of the type BC547C. The circuit is similar to Darlington scheme. Each transistor amplifies the current approximately 500-times, so the total amplification factor may be about $2.5{\cdot}10^5$. The LED needs just the current of the order of mA its light to be visible. Therefore this device can indicate the currents of the order just several nanoamps flowing to the terminal A. Initially this type of circuit was meant to indicate the connection of + and A terminals even by dry hands but it occurred that it is sensitive enough to indicate also changes of electrical field.

To make the indicator as transparent as possible it is useful to build it at a piece of wooden board with small brass nails hammered into it, to which terminals of transistors and other components are sold.

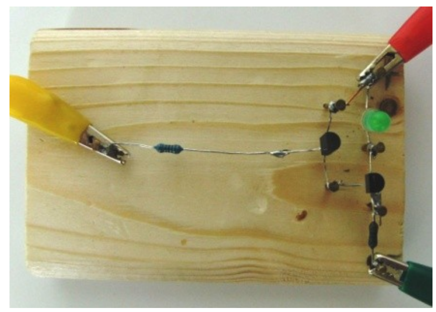

FIGURE 10. The constriction of the indicator clearly reveals its circuit diagram and function.

How to determine the sign of some charge by this indicator? First, students should find that the LED shines if the terminal A is connected to the + pole (and does not shine when connected to the – pole), *i.e.*, that it shines when the current is flowing *into* the terminal A (and the base of the transistor T1).

Then, if we move a *positively* charged object closer to a terminal A it will repulse positive charges, these will go to a base of the transistor T1, it means that there will be a current flowing to the base of T1. So, the LED will glow. Of course, no positive charge will move in metal conductors but the electrons will move to the terminal A. It is up to teachers when and to which depth they will discuss this with their students.

If we bring a *negatively* charged object (for example a plastic rod or a straw) closer to the terminal A the electrons will be repulsed, it means a positive charge will accumulate at A. When we then move a negatively charged rod *away* from A, the charge (*i.e.*, the current) will flow into the base of T1 and the LED will glow.

Note: The same indicator with PNP transistors will behave just in the opposite way.

The indicator is sensitive enough to react to the motion of a charged straw at a distance of several centimeters. Attaching a short cable to the terminal A increases the sensitivity. It can be increased further (and substantially) by grounding any terminal of the battery attached to the indicator. Still greater sensitivity can be achieved by connecting the terminal A to somewhat larger conductive object, for example a small can on an isolated base. Then the LED indicates movements of a larger charged rod at a distance more than one meter.

Of course, this indicator can be used also for other experiments, for example for demonstration of charging and discharging of a small capacitor made from two aluminum foils and a plastic foil.

This circuit can be also used as an inspiration for various small students' projects. For example, an indicator with three bipolar transistors can be constructed with a small light bulb instead of LED. (Such a construction was shortly mentioned in [5]). And various other modifications of a basic circuit are possible making it a suitable tool that can be used in IBSE type teaching and learning.

V. HOW LARGE IS THE CHARGE?

The concept of charge is typically introduced very early in electrostatics. But try to ask students how large is a charge, for example of a charged straw or plastic rod. Even short informal inquiry can reveal that the estimates vary by orders of magnitude. Also physics teachers and educators when asked to give a quick estimate of the value of charge are often not much better. I asked participants at sections of two physics education conferences (20-30 people in each case) to provide the estimate of the value of such charge – and the estimates ranged from hundreds of picocoulombs to nearly a millicoulomb. It means the discrepancy of more than six orders of magnitude! Of course, I quote here the extremes but the differences of three orders of magnitude were rather typical. It seems the charge is one of quantities about which values we have the worst "physics intuition". (Compare it to the length – no group of people would give the estimates of the length of the straw from one centimeter to ten meters not speaking of extremes one millimeter and one kilometer.)

Surprisingly, even very simple experiment shown above at Fig. 3 can give at least a rough estimate of a value of charge at the straws. Using Coulomb's law

$$F = k \cdot \frac{Q_1 Q_2}{r^2},$$

where k [illegible] $^2/\mathrm{C}^2$, and assuming that the charges of both straws are approximately the same we immediately arrive to the resulting formula

$$Q = r\sqrt{\frac{F}{k}}$$

In our experiment the electrostatics repulsive force F balances the weight mg of the straw. The mass of a straw is approximately 0.5g (students can measure it by scales). For the distance r of straws being 2cm the formula gives the value of charge Q about 15 nanocoulombs. So, our rough estimate gives the values of charges of straws of the order of tens of nanocoulombs.

All these estimates can be done at high school level. Of course, student might (and should) protest that Coulomb's law holds for point-like charges whereas the straws are rather charged lines. However, the more detailed analysis (see [4]) shows that our rough estimate is surprisingly good: for r = 2cm it gives nearly 50% of the exact value (for two homogeneously charged straight lines). For greater r the discrepancy is even lower. The exact calculation can be done at introductory university level. At high school level the model of a straw as a series of point charges and the calculation of the force using computer can help. (It will be presented elsewhere since in this article we concentrate only on simple experiments and calculations).

VI. ELECTROSTATICS AND CURRENTS: LOW-COST MEASUREMENT

If we charge some object, for example a can on an isolation base (*e.g.* a piece of Styrofoam), we can then discharge it slowly by touching it for example by not too dry wooden skewer. A piece of aluminium foil hanging at the side of the can shows us (by its graduate decline) that discharging is really slow, lasting for seconds.

Charge flows through the skewer in this experiment – it means an electric current is present. An interesting problem arises naturally: Could we measure this current by some simple experiment? Of course, the current is very small: the total charge of a can being tens of nanocoulombs and the characteristic time discharging is of order of seconds the value of current would be of order of nanoamps or tens of nanoamps.

Again, perhaps also a bit surprisingly, such measurement can be done, in this case using an ordinary cheap digital multimeter. Students may be surprised that this is possible because the multimeter can usually measure currents of the order of microamps or more. But there is another possibility: To use voltage ranges. The internal resistance of a digital multimeter as a voltmeter is typically 10MΩ. (The cheapest models have internal resistance just 1MΩ, they are less convenient for our measurement but still usable.) The current 1nA=10^{-9}A at the resistance 10^7Ω produces voltage 10^{-2}V=10mV. It can be easily measured by a digital multimeter. In fact, quite often the sensitivity at the most sensitive range (up to 100mV) is just 0.1mV. It means that a digital multimeter can detect and measure currents as low as tens of picoamps!

Experiments like this can help to persuade students that the "electricity" in electrostatic experiments is the same as the "electricity" that powers the light bulbs, LEDs etc. At an introductory university level we can even measure how the current discharging the can depends on time – and to show that it decays exponentially.

VII. CONCLUSIONS

Most of experiments described in this article can be used at various school levels from elementary to introductory university and in both pre- and in-service training of physics teachers. Here, deliberately, the simplest and cheapest experiments were presented. Nevertheless, they proved to be useful for introducing basic concepts of electrostatics and investigating its properties. As it was stated above, teachers can easily use different variants of these experiments or adapt them to suit the needs of their own teaching.

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