www.iop.org/journals/physed

Microscopic models for bridging electrostatics and currents

L Borghi, A De Ambrosis and P Mascheretti

Dipartimento di Fisica ‘A Volta’, Università di Pavia, Italy

E-mail: borghi@fisicavolta.unipv.it

Abstract

A teaching sequence based on the use of microscopic models to link electrostatic phenomena with direct currents is presented. The sequence, devised for high school students, was designed after initial work carried out with student teachers attending a school of specialization for teaching physics at high school, at the University of Pavia. The results obtained with them are briefly presented, because they directed our steps for the development of the teaching sequence. For both the design of the experiments and their interpretation, we drew inspiration from the original works of Alessandro Volta; in addition, a structural model based on the particular role of electrons as elementary charges both in electrostatic phenomena and in currents was proposed.

The teaching sequence starts from experiments on charging objects by rubbing and by induction, and engages students in constructing microscopic models to interpret their observations. By using these models and by closely examining the ideas of tension and capacitance, the students acknowledge that a charging (or discharging) process is due to the motion of electrons that, albeit for short time intervals, represent a current. Finally, they are made to see that the same happens in transients of direct current circuits.

Introduction

It is well documented in the literature that high school students are not able to link concepts of electrostatics to their description of the phenomena occurring in electric circuits (Tiberghien 1984, Closset 1989, Benseghir and Closset 1996). This leads to a concept of voltage which remains so vague that it is not utilized operationally and that a consistent picture is not created to explain the observed phenomena. Moreover, according to Eylon and Ganiel, ‘the absence of a micro–macro link impedes students’ ability to conceptualise the electric circuit as a system and to appreciate the functional relationship between its parts’ (Eylon and Ganiel 1990). A study, carried out with prospective elementary school teachers to explore their models for charging insulators and their evolution while studying static electricity, shows how long the process of building coherent models can be (Otero 2004). The conceptual difficulties that university students come across in understanding the process of the electrical charging of a body have been investigated by Guisasola *et al* in a study involving students attending the first and third year of an engineering degree course (Guisasola *et al* 2005).

Different approaches have been proposed to help students create a representation of the mechanism underlying the flow of current, based on an analogy with mechanical systems (Hartel 1982, Steinberg 1985, Licht 1987). We think that the effectiveness of this kind of work could

0031-9120/07/020146+10$30.00

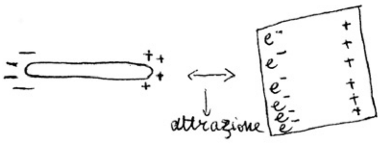


Figure 1. A drawing representing the idea that rubbing produces a separation of charges.

be enhanced by a wide preliminary experience of electrostatic phenomena. More precisely, we believe that a better understanding of electricity can be obtained by focusing attention on the microscopic models used to interpret electrostatic phenomena, starting from the analysis of simple experiments, some of them related to the historical origin of the idea of voltage and of capacitance. This, in our opinion, can favour the development of a link between electrostatics and circuits (Arons 1997), by pointing out the role of voltage in determining the motion of electrons.

We have developed a teaching proposal based on the results of preliminary work carried out with prospective physics teachers, which aims to identify the models they use to explain electrostatic phenomena (Borghi *et al* 2005).

First, the results of this work are briefly reported, then the main points of the teaching sequence we have developed are described.

Preliminary inquiry

The work involved 30 student teachers enrolled at the University of Pavia in a school of specialization for teaching mathematics and physics in a secondary school. The majority (21) were graduates in mathematics (in Italy both graduates in mathematics and in physics may attend this school of specialization).

Initially, we proposed that our student teachers carried out simple experiments in the laboratory dealing with interactions between charged objects. They worked in groups and were requested to write down what they observed and to propose interpretations consistent with their observations (possibly with the help of drawings). Our aim was to engage them in the construction of models to explain the phenomena observed. We were able to obtain information on the student teachers' ideas by observing their work and by analysing the written material they produced. In particular, the student teachers' worksheets showed the following convictions and difficulties:

- Some of them (9) did not discriminate between observations and interpretations. For example, in describing the results of their experiments they used the following statement: '*one observes more positive charges on the side of the metal rod near to the negative plastic rod*'.
- They referred, in general, to positive and negative charges, and a number of them (20) did not mention the electrons as the charges displaced from one material to another by rubbing.
- Twelve shared the idea that rubbing separates charges. Figure 1 shows a drawing extracted from a worksheet.

The students' comment was: '*Rubbing makes the plastic rod positive and the wool negative. The consequence is attraction between the two objects*'.

They did not realize that their drawing showed two neutral bodies which would repel each other if one of them were rotated by 180°. An example of the same kind is shown in figure 2.

The idea that rubbing '*generates*' positive or negative charges was expressed by three student teachers who seemed to ignore basic ideas on the properties of matter.

Many student teachers had difficulty explaining the behaviour of metals. They expressed the following ideas:

- In a metal, both positive charges and negative charges move. Figure 3 shows a brass (*ottone* in Italian) rod near to a charged plastic (or glass) one; A and B indicate positive and negative charges;

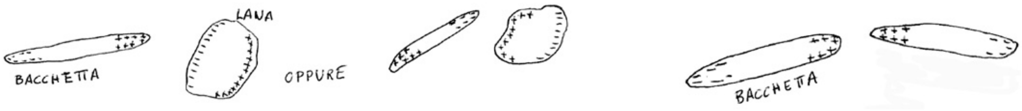


Figure 2. Another example of 'separation of charges'.

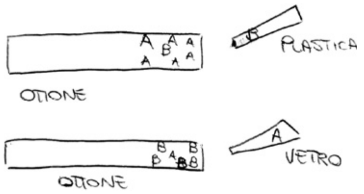


Figure 3. In this drawing positive (A) and negative (B) charges are considered equivalent.

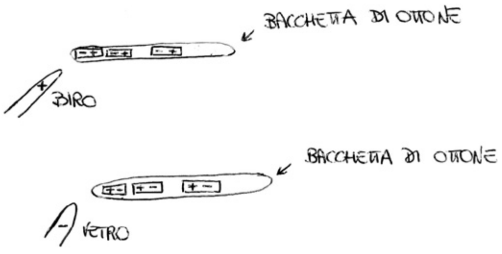


Figure 4. This drawing reveals the idea of polarization at a molecular level in a metal.

- A charged rod 'polarizes' molecules in a metal (figure 4).

  Moreover:

- Eight student teachers did not give interpretations of the attraction between a charged rod and a neutral metallic rod. All of them were in the group of students who had not mentioned electrons in their previous explanations;
- Metallic objects cannot be charged by rubbing;
- The idea that a wooden rod cannot interact with a charged object is shared by a number of student teachers who explain their conviction by affirming that wood is a *real insulator*.

All these ideas show student teachers' difficulty in interpreting electrostatic phenomena within the framework of their knowledge of the structure of matter, and seem to be a serious obstacle to understanding not only electrostatic phenomena but also the properties of electric current and circuits.

A critical analysis of the models proposed was carried out with the student teachers to construct shared microscopic models consistent with the experimental results.

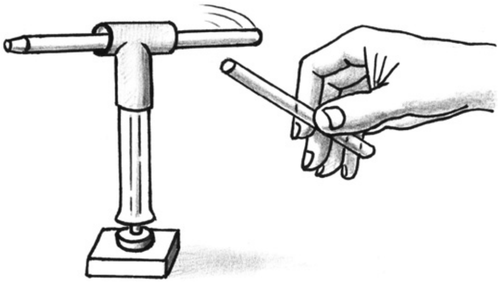


Figure 5. The device used to reveal electrostatic forces: the interaction between two charged rods makes the system rotate.

This activity helped us to focus on the student teachers' main difficulties and to devise a sequence that was able to enhance their understanding of electrostatic phenomena, to promote modelling processes for their interpretation and to favour the perception of continuity with the phenomenology of circuits.

Steps in the teaching sequence

In the following, the main aspects of a teaching sequence devised for high school students are presented by focusing, in particular, on the experiments we propose. The sequence is structured in phases, dealing with charging objects by rubbing and by induction, constructing microscopic models to interpret electrostatic interactions, finding formal models, and relating electrostatics to currents.

Electrostatic interactions

In order to explore electrostatic phenomena we prepared a device based on the idea of a tool (named 'versorius') used at the onset of the development of electrostatics. It allows us to visualize the effects of the small forces we want to explore. It can easily be constructed by capping the blind extremity of a test tube (1.5 cm diameter and length approximately 15 cm) with a tube made of cardboard, carrying, perpendicular to its axis, a smaller tube through which rods made of different materials can be inserted. The whole apparatus, placed vertically on a pencil, itself attached to a stand, is free to rotate around its axis (see figure 5).

With this system one can check how rods of different materials interact, after they are charged

Figure 6. Studying the electrostatic force.

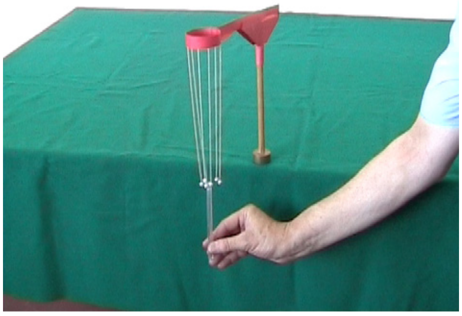


Figure 7. The symmetry of the electric interaction.

by rubbing them with a woollen cloth, and, in particular, one can investigate the interactions between two charged insulators or the interaction obtained when an uncharged metallic rod replaces the charged insulator.

To get an idea of the value of this interaction and to show its dependence on the distance between the charged objects, the device shown in figure 6 is used. The experiment shows that the intensity of the force increases when the distance diminishes.

In order to visualize the spatial distribution of the forces produced by a charged object and to suggest the idea of force field, the simple device shown in figure 7 is proposed.

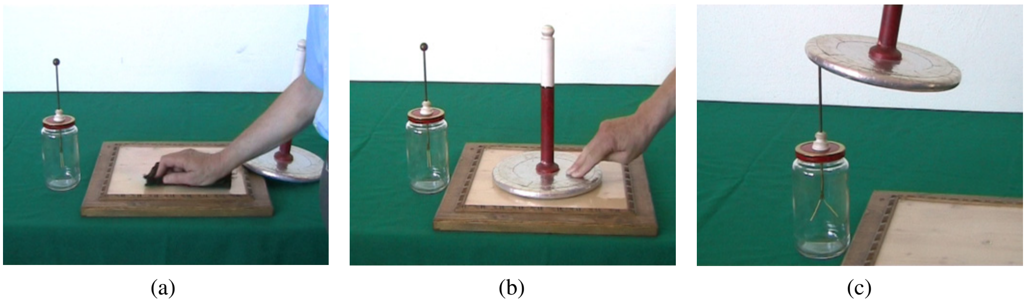
Light plastic balls, covered by a metallic sheet, hang from thin threads to form a circle. When a charged plastic rod is placed close to the centre of the circle, each ball experiences a force directed towards the rod (due to induction in the metallic sheet). The motion of the balls suggests the symmetry of the force distribution around the charged rod.

Induction can also be observed in uncharged insulators (for example in a wooden rod inserted in the versorius) and even in water (for example, drops falling from a syringe near to a charged plastic rod).

Further exploration of electrostatic phenomena was carried out with traditional apparatus—electrostatic machines and Leyden bottles (made with glass jars and aluminium sheets)—to verify how these devices allow one to collect a considerable number of electric charges and to produce sparks. Particular attention was devoted to the electrophorus (figure 8) because the interpretation of its functioning as a charging process by induction requires reflection on the role of free electrons in metals.

Microscopic models

Students are requested to propose models to interpret the observed phenomena based on their knowledge of the structure of matter. They



(a) (b) (c)

Figure 8. The electrophorus (a) and the process of charging a metal by induction (b). An electroscope is used to detect electric charges on the disc (c).

are guided towards controlling the coherence of their models and to focusing their attention on the different behaviour of electrons in insulators and in conductors. From this point of view, the interpretation of the functioning of an electrophorus is a test of the understanding of the charging processes acquired by the students.

At this stage we suggest the use of software designed to visualize electrostatic phenomena. The effectiveness of visualization software in promoting the integration of macroscopic and microscopic perspectives in electrostatics is well documented in the literature (see, for example, Casperson and Linn 2006). For this purpose we prepared animations visualizing charging by the rubbing process in insulators and the displacement of free electrons in metals due to interaction with charged objects.

Formal models

Another way of looking at electrostatic phenomena is to consider the energy involved. The existence of an electrical interaction between charged objects implies that work is done when the distance between them varies. For example, in the case of figure 7, the work results in an increase of the gravitational energy of the little balls. This work corresponds to the change of the electrical potential energy associated with a given configuration of the system.

Then, we can describe the charging of objects as a process increasing their electrical potential energy, and interpret the results of the experiments described above as being due to the general rule that an isolated system tends to reach the configuration of minimum potential energy spontaneously.

In particular, we propose to reflect on the case of an electroscope: when it is charged, its foils diverge. This can be interpreted both as a balance of gravitational and electrical forces and as a condition of minimum potential energy in the system. The increase in gravitational energy is, in fact, accompanied by a decrease in the electrical energy and, in the equilibrium condition, the total potential energy (gravitational and electrical) is minimum. Thus, the observed divergence of the foils is connected both to the intensity of the repulsive forces and (through the elevation of the centre of mass) to the variation in the electrical potential energy of the system. Volta used the word *tension* to express the particular condition of the charge configuration producing divergence of the foils, and evaluated it by measuring the angle formed by the foils of the electroscope. Actually, *tension* is a variable connected to the electrical potential energy of the system.

The other parameter necessary to define the energy of a system is its *capacitance.* To introduce this idea, we suggest the use of an electroscope in which the ball is substituted by a metal disc (figure 9(a)). When the electroscope is charged, for example by touching the lower face of the metal disc with an electrophorus, the two thin foils diverge (figure 9(b)). By putting on the electroscope a disc of marble (or chalk), the two foils approach each other (figure 9(c)), revealing that tension diminishes. Since the total charge on the electroscope does not change, the new condition of the system has to be described by means of a new physical quantity, the *capacitance* (*capacità* in Italian), a term used by Volta (Volta 1782) to express the ability of the system to receive more charge[1].

In order to suggest an interpretation of the electric quantities, Volta used analogies with different mechanical systems. The lower panel of figure 9 is a sketch of a hydrostatic analogy. It suggests that the disc of marble put on the electroscope decreases the tension of the system by increasing its capacitance in the same way as the increase in the base of a vessel causes a decrease in the water level. The correspondence between the electrical parameters and the terms used in the analogy is shown in table 1.

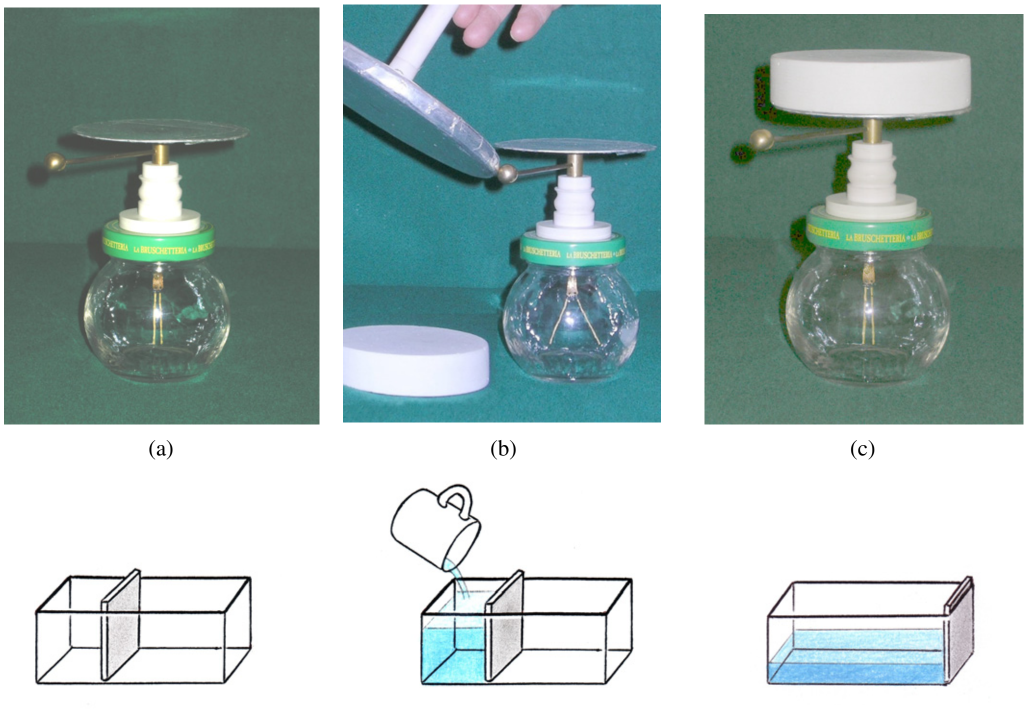
By using analogies of this kind, Volta proposed a quantitative relation between charge, tension and capacitance[2]:

$$Q = VC. \qquad (1)$$

---

[1] In the same period, though in a different cultural frame, Henry Cavendish (1731–1810) carried out experiments on charged bodies of various sizes and shapes, connected by metallic wires. He argued that electrically connected bodies carried charges at the same 'degree of electrification' and concluded that the ratio between the number of charges should have a physical meaning. In this way he introduced the idea of 'electrical capacity' and set up methods to obtain precise measurements of it (Cavendish 1921). Maxwell's 1879 edition was reprinted by Frank Cass in 1967.

[2] It is worthwhile noting that Volta exposed this relation for the first time in his lectures at the University of Pavia in 1784 (Fregonese 2002).



(a) (b) (c)

Figure 9. Changing the capacitance of a system: (a) neutral electroscope (empty vessel); (b) charging the electroscope produces a tension (water, poured into the narrow vessel, reaches a given level); (c) increasing the capacitance makes tension diminish and the possibility of acquiring other charges increase (shifting the mobile wall makes the area of the base of the vessel increase and the level of the water drop: more water can be poured in).

Table 1. Correspondence between the electrical parameters and the terms used in the hydrostatic analogy shown in figure 9.

Electrical parameter	Parameter of the liquid
Charge Q	Volume of liquid
Tension V	Height of the level
Capacitance C	Area of the base of the vessel

This relation can be experimentally verified, and it defines the capacitance of a system as the constant ratio between charge and tension.

The analogy also allows acknowledgment of the relation between tension, charge and energy.

The gravitational energy of a mass m of liquid in a cylindrical container in which the level is h is $E_g = mgh/2$ (the centre of mass of the liquid is at a height $h/2$). Then, according to the analogy, the electrical potential energy is

$$E_e = QV/2. \tag{2}$$

This allows an interpretation of the tension V as the intensive variable controlling the variation of energy for a given variation, i.e. transfer, of charge. For this reason V was also named the *electrical potential* of the system.

Charges in motion

In order to show that a difference in tension drives the motion of electrons in conductors, we propose the experiment represented in figure 10.

Initially, the metallic discs of two identical electroscopes are equally charged (figure 10(a)). Then they are separated and, as previously, a disc of marble is placed on one of them (figure 10(b)). Now the two electroscopes reveal different tensions (with charge unchanged). If we connect them, we can see that an equilibrium is reached, with the foils of the electroscopes diverging equally, i.e. the tension is the same (figure 10(c)). The *difference in tension* drives the electrons from one disc to the other. Now the disc

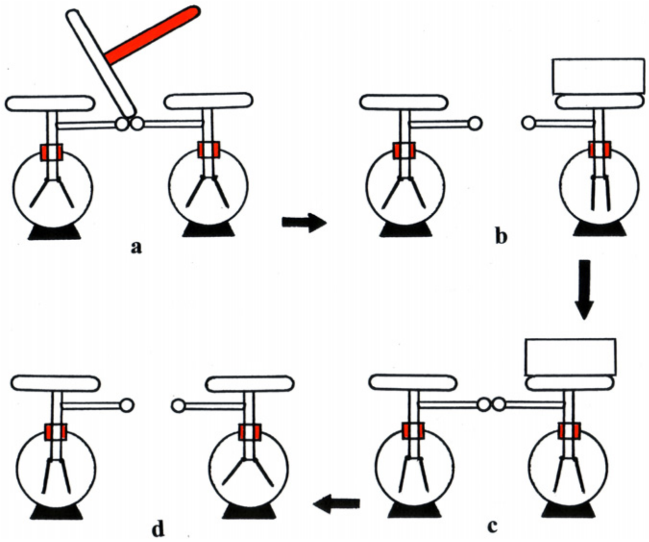


Figure 10. Tension drives the motion of electrons.

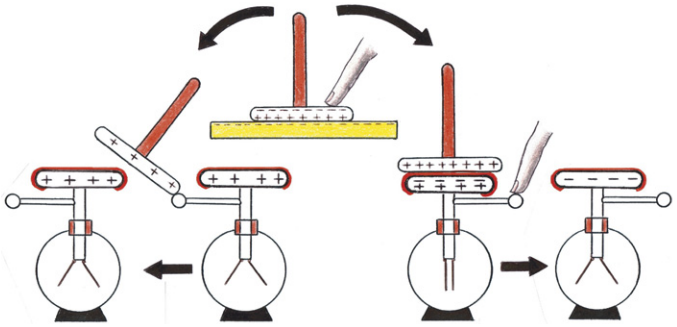


Figure 11. Charging two electroscopes with an excess and a reduction of electrons.

covered by marble has more charge than the other one, as is apparent by removing the cover and by noting the angle between the foils (figure 10(d)).

Now the problem is as follows: is there a difference between a ‘tension’ due to an excess of electrons and a ‘tension’ due to a reduction of electrons? The divergence of the foils does not discriminate between the two cases. It is easy to see that if one disc is charged positively and the other one negatively (so that the foils are equally diverging), when they are connected, the foils drop, showing that their initial tensions were different.

Figure 11 shows how to produce an excess of electrons on one conductor and a reduction on another one, by using induction. Two electroscopes are used, with the upper surface of the discs covered by a thin film of insulating material.

Thus, tension is an intensive variable, characterized by positive and negative values, so a difference in tension can be obtained by adding electrons to a metallic object and by subtracting electrons from another one.

Tension is defined as positive when it is due to depletion of electrons, and negative in the other case; thus electrons move towards positive tension.

From electrostatics to currents

In order to link the concepts of charge, tension and capacitance (acquired in an electrostatics

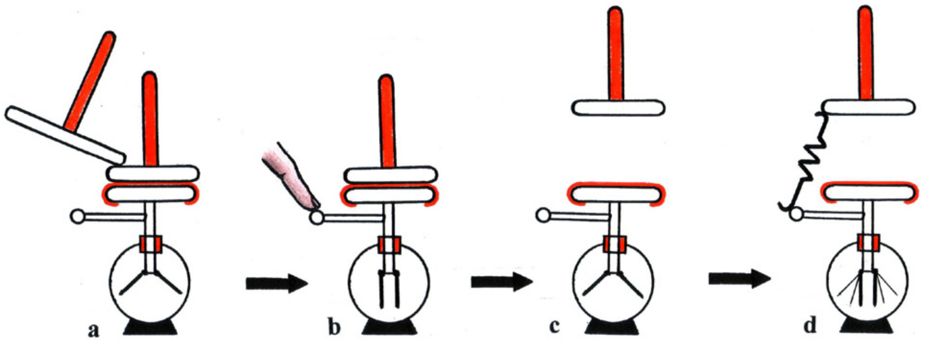


Figure 12. In (a) and (b) two metallic discs are charged. The system is a capacitor with variable capacitance. In (d) a current discharges the capacitor.

framework) to electrokinetics phenomena, a system of two metallic discs forming a capacitor is studied.

A metallic disc, with an insulating handle, is placed on an electroscope (covered by an insulating film) and charged (figure 12(a)). The electroscope is then charged by induction (figure 12(b)), so that the two discs acquire opposite charges and potentials.

This system is a capacitor: for a given distance between the discs the *capacitance* of the system is defined as the ratio between the *charge* on each disc and the *potential difference* between the two discs: $C = Q/\Delta V$.

In the configuration shown in figure 12(b) the system has high capacitance and low potential difference, as the inappreciable divergence of the foils shows. But, when the upper disc is lifted (figure 12(c)), the capacitance drops, with a corresponding increase in potential difference.

If the two discs are connected by means of a resistor (about 10 MΩ), the foils drop and their movement lasts an appreciable time interval (figure 12(d)). The discs and the resistor constitute a ‘circuit’ in which a potential difference produces, for a short time, an electric current.

At this point, we introduce a typical circuit device able to charge the capacitor by transferring electrons directly from one disc to the other: a battery.

A battery can be considered as a system that maintains its two metallic terminals at a constant *difference in tension* (or *potential*) because of chemical reactions taking place in its interior.

Then, if the terminals of a battery are connected by wires to the neutral discs of a capacitor (figure 13(a)), electrons flow from the terminal at *lower potential* to one disc and from the other disc to the terminal at *higher potential*. Figure 13(b) shows that the battery has actually charged the capacitor (now disconnected from the battery), because a divergence of the foils is produced when the capacitance is diminished.

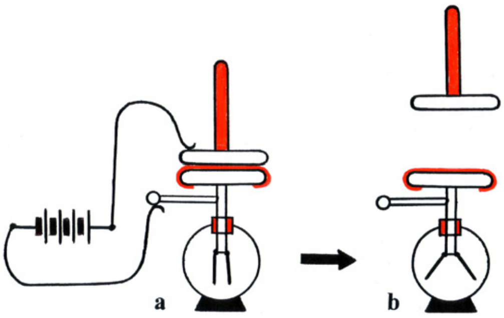


Figure 13. A capacitor is charged by means of a battery.

This is a critical point because, as Benseghir and Closset (1996) affirm, it must be pointed out that the capacitor is not charged simply by the small number of charges on its terminals, but because the battery keeps a constant difference of potential between its terminals. Thus it continuously feeds one terminal with electrons by taking them away from the other one. In the case considered, the charging process of the capacitor stops when the potential difference between the two discs equals that of the battery.

If a closed circuit connects the terminals, the potential difference of the battery drives electrons until the chemical processes are exhausted.

These experiments show that electrostatic effects can be obtained by means of a battery, while currents can be obtained, albeit for short time intervals, by means of electrostatic devices.

From the point of view of energy, both a charged capacitor and a battery can be considered energy storage devices (electrostatic and chemical, respectively); this energy is available when the potential difference between their terminals can drive a current.

We think that it is very important to focus on transient phenomena, like the ones just considered, to link electrostatics to circuits. But this requires, as Thacker *et al* (1999) pointed out, the development by students of microscopic models to explain, in a qualitative way, the mechanisms leading to the observed phenomena.

Conclusions and implications

Starting from the student teachers' difficulties in understanding electrostatic phenomena and in proposing models to explain simple experiments, we developed a teaching sequence aimed at promoting the development of a microscopic model to explain, in a consistent way, a variety of different phenomena.

For that, we used experiments and interpretations close to historical ones, but we proposed a structural model based on the particular role of electrons as elementary charges both in electrostatic phenomena and in currents. Recent trials of parts of the sequence with student teachers showed that it is convenient:

- To encourage students in developing a microscopic model to interpret the results of their observations. Doing experiments in electrostatics is amusing and, at the same time, very demanding when the goal is the construction of coherent explanation models;
- To propose experiments similar to those used historically at the beginning of electrostatics studies so that students are engaged in building basic concepts and the first formal descriptions;
- To use analogies with other phenomena already known by the students to help them identify the significant variables and their relationships;
- To use the microscopic model to create continuity between electrostatics and currents, by focusing on the movement of electrons in transients both in electrostatics and in direct current electric circuits;
- To consider electrostatic phenomena from the point of view of energy. This contributes to ensuring a significant connection between electrostatics and currents.

The next step will be testing the teaching sequence with high school pupils. It will then be possible to get information on its effectiveness and to focus on the reactions of teachers in dealing with the subject in the classroom.

Acknowledgments

We wish to thank all the student teachers participating in the work. The research was supported by the Italian Ministry of Instruction, University and Research.

Received 28 July 2006, in final form 14 December 2006
doi:10.1088/0031-9120/42/2/003

References

Arons A 1997 *Teaching Introductory Physics* (New York: Wiley)

Benseghir A and Closset J 1996 The electrostatics–electrokinetics transition: historical and educational difficulties *Int. J. Sci. Educ.* **18** 179–91

Borghi L, De Ambrosis A and Mascheretti P 2005 Working on electrostatics with prospective teachers *ESERA Conf. (Barcelona)* pp 783–6

Casperson J M and Linn M C 2006 Using visualization to teach electrostatics *Am. J. Phys.* **74** 316–23

Cavendish H 1921 *The Scientific Papers of the Honourable Henry Cavendish* vol 1 *The Electrical Researches* ed J C Maxwell (rev J Larmor) (Cambridge: Cambridge University Press)

Closset J L 1989 Les obstacles à l'apprendissage de l'électrocinétique *Bull. Union Phys.* **716** 931–50

Eylon B and Ganiel U 1990 Macro–micro relationship: the missing link between electrostatics and electrodynamics in students' reasoning *Int. J. Sci. Educ.* **12** 79–94

Fregonese L 2002 Le invenzioni di Volta tra teorie ed esperimenti *Gli strumenti di Alessandro Volta* ed G Bellodi, F Bevilacqua, G Bonera and L Falomo (Milano: Hoepli) pp 73–120

Guisasola J, Zuminendi J L, Almudi J M and Ceberio M 2005 *ESERA Conf. (Barcelona)* pp 1080–3

Hartel H 1982 The electric circuit as a system: a new approach *Eur. J. Sci. Educ.* **4** 45–55

Méheut M and Psillos D 2004 Teaching–learning sequences: aims and tools for science education research *Int. J. Sci. Educ.* **26** 515–35

Otero V K 2004 Cognitive processes and the learning of physics, part I: The evolution of knowledge from a Vygotskian perspective *Proc. Int. School Phys. Enrico Fermi, Course CLVI: Research on Physics Education* ed E F Redish and M Vicentini (Amsterdam: IOS) pp 409–45

Steinberg M S 1985 Construction of causal models: experimenting with capacitor controlled transient as a means of promoting conceptual change *Aspects of Understanding Electricity: Proc. Int. Workshop* ed R Duit, W Yung and C W Rhoneck (Kiel: IPN) pp 363–73

Thacker B A, Ganiel U and Boys D 1999 Macroscopic phenomena and microscopic processes: student understanding of transients in direct current electric circuits *Am. J. Phys.* **67** S25–31

Tiberghien A 1984 Revue critique sur les recherches visant à élucider le sense des notions de circuits électriques pour des élèves de 8 à 16 ans *Recherches en Didactique de la Physique, Les Actes du premier Atelier International: la Londe les Maures* (Paris: CNRS) pp 91–107

Volta A 1782 Del modo di rendere sensibile la più debole elettricità sia naturale, sia artificiale *Le opere di Alessandro Volta, Edizione Nazionale* 7 vol (1918–1929) (Milano: Hoepli) pp 288–9

Lidia Borghi, Anna De Ambrosis and **Paolo Mascheretti** are professors of physics at the Universiy of Pavia, Italy. They are actively involved in researches on scientific education in primary school, physics education in high school and teacher preparation, particularly with the use of computers.