Chapter 47
An Experimental Approach of Nodes Towards the Electric Potential for Students and Teachers

Alessandra Mossenta and Marisa Michelini

Abstract Electricity is a common learning topic. Early research on students' difficulties on circuits pointed out that the concept of potential does not have role nor meaning and referred it to the link between electrostatics and circuits. Subsequent research highlighted how potential is not recognized as a significant quantity for charge transfer or in activities to bridge electrostatics and circuits, micro and macro view. Starting from these outcomes a teaching/learning proposal was designed on charge transfer with simple hands-on experiments and sensors. It aims at realizing the students' cognitive need for an interpretative quantity (potential) driving the charge transfer, with a meaning of energy.

$$S_{i,j}^{m,t} = (1-\alpha)S_{i,j}^{m,t-1} + \alpha S_{i,j}^{n,t,u,v}$$

47.1 Introduction

Static electricity forms part of our daily experience, concerning both natural phenomena (e.g. discharging by sparks) and technological devices (e.g. functioning of photocopiers).

The role of education, to provide students of tools to organize phenomenology and to build models for its interpretation and for a sound approach to everyday challenges, implies the need to take into account also this topic. From the educational point of view, electrostatics has a central role in electromagnetism as a fundamental context where charge, field and potential concepts are introduced and principles as the conservation of charge and the superposition principle organize the interpretation of phenomenology. On a methodological plane, electrostatics could provide a fertile

A. Mossenta (✉) · M. Michelini
University of Udine, Udine, Italy

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context where the process of building scientific knowledge as an activity of model development, starting from and based on phenomenology, could be exemplified.

A broad research on learning difficulties (Pfundt 2009), pointed out that for the students' perspective, the concept of potential (along with the related concepts of potential difference and fem) does not have a role in the operation of electric circuits nor a separate meaning justifying its use as an interpretative quantity [2, 3]. According to the first studies about the reasoning on circuits [2–4], students identify and/or not relate adequately potential difference with current and potential, analysing circuits with sequential and local reasoning. Potential is not associated with an electric field and/or forces. Students do not relate current, in its macroscopic manifestation, with the microscopic phenomenon of charge motion. A suggested solution was to connect electrostatics and electrodynamics, via microscopic models. Other researches relate the learning difficulties to a reuse of the previously acquired electrostatics knowledge in an unchanged form [5], potential difference corresponding to a difference in the local density of mobile charges at the circuits points considered. Subsequent research concerned both proposals of teaching/learning sequences designed to build links between microscopic view in electrostatics and macroscopic view of the electric circuits [6–8], and studies of the students' reasoning in interpreting electrostatics phenomena [9, 10]. As concerns the high school and university students' description in explaining electrostatics phenomena, four models of electricity were identified [9]. According to the most popular model, electricity is a fluid that passes from one body to another: through rubbing it passes only on to dielectrics; through contact, it passes only on to conductors. Researches on students' understanding of the transfer of charge between charged conductors [10] pointed out that students admit a transfer only between oppositely charged conductors until one of the conductors became neutral (according to the rule 'like charges repel'). Primary-school student teachers explained the charge transfer between two identical metal spheres with the different quantities of electrons on them, freely interchanged with the difference in potentials [6], and a process of electrons moving from the sphere with the greater number to that with the lesser, until both spheres obtain the same charge. Researches on university students' reasoning linked to the use of electrical potential and capacitance in the processes of electrical charging of a body [11–13] confirmed the previous model and pointed out that students attribute to the potential the meaning of "indicator of quantity of charge" which the body can contain, establishing an identification between charge and potential. The capacitance is identified with the charge, as if the body were a recipient that admits a certain quantity of charge depending on its size, or it is understood as the facility to drive the charge. When reasoning include Coulomb's force, a certain identification between electric force and electric potential is produced.

Some proposals focused in the domain of electrostatics for high school or university students were developed to overcome the learning difficulties, in the perspective of linking electrostatics and electrodynamics, a microscopic with a macroscopic view. Borghi et al. proposed a teaching sequence based on the use of microscopic models to link electrostatic phenomena with direct currents. Starting from experiments on charging objects by rubbing and by induction closely examines the Volta's ideas of tension and capacitance to make the students acknowledge that a charging process is due to the motion of electrons representing a current. Tension is considered as the particular condition of the charge configuration producing divergences of the foils of an electroscope and capacitance as a magnitude expressing the ability of the system to receive more charge. The sequence developed by Guisasola et al. [14], takes into account the historical concept of capacitance in phenomena of body charging, for a transition from electrostatics to electrokinetics, helping students establish connections between the movement of charges (microframe) and an energy analysis of the system (macroframe). As a result of the implementation of the proposal, authors found that many students seemed not to relate the processes of charging to other electrostatic concepts such as potential or field. Moreover, students did not develop model-building skills to the hoped level. The authors connect this problem to the previous research, suggesting that scientific reasoning skills are difficult to develop without a curriculum specifically aimed at giving students practice in engaging in scientific activity.

47.2 The Vertical Proposal on Electrostatics

Our activity focused on a vertical sequence, offering possibilities to develop scientific content and methodological skills to the pupils since their first explorations of phenomenology, to build scientific concepts and methods when their interpretative models are build first. This could provide pupils with scientific ideas avoiding the need of a change of their spontaneous ideas when they are deeply inserted in a spontaneous way of reasoning, during high school or university.

We developed a learning proposal starting from learning and conceptual knots emerged from literature, in the theoretic framework of the Model of Educational Reconstruction [15]. A first part of the proposal is focused on the macroscopic properties of the electric interactions, to build the first level of interpretation of the electrostatic phenomena yet at Primary School level. In this phase we aim to produce the need to introduce an interpretative entity, the charge, to give sense to phenomena observed during electrical interactions emerged in charging processes of several materials; the properties of dual nature and mobility also emerge from phenomena interpretation. Following this first part, a quantitative activity was proposed, focused on interpretation of the movement of charge and its transfer by rubbing and by contact. The measure of charge involved in the process aims to introduce the concept of potential, to give it a role of driving the charge transfer and a meaning of work to do it; the measurements aim to give evidence also of charge conservation. The proposal is organized as a sequence of explorative hands-on activities with explorative stimulus-worksheets [16, 17] to drive the development of a coherent building of macroscopic models then substituted by microscopic models; when implemented, a strategy of Conceptual Microsteps based up SPEA cycles (Situation, Prevision, Experiment, Analysis) is proposed, to give to the students methodological tools in training the scientific methods aspects. The sequence is designed also to be proposed to prospective Primary School teachers, during their education to develop their Pedagogical Content Knowledge [18]. We report the first outcomes of an implementation of the sequence with middle school and high school students.

47.3 The path

The first qualitative part of the proposal can briefly be summarized as follows:

Pulling and rubbing: Observed macroscopic interactions between couples of objects pulled off the same/different surfaces or rubbed with the same/different material aims to build the concept of electric state of objects linked to a macroscopic property responsible for the interactions. The two kinds of interaction are attributed to the relation between two kinds of property, each of which can be assumed by each object.

The couples: The attraction of two objects modified one with the other by pulling or rubbing gives a first appearing of the idea that charging is an effect of an interaction, in which both objects of the couple involved in pulling or rubbing are modified, resulting in different states.

An electric state detector: A simple detector made of strips of adhesive tape, pulled apart after being stuck together, allows to increase the kind of objects that can be electrified by rubbing (insulators and metals), gives evidence that the effects of pulling and rubbing are referred to the same origin (differently from magnetic effects) and brings out the conclusion that there are only two kinds of electric state. Observing many interactions leads naturally students to assume the dependence of the interaction from distance and level of modified state.

A can: Repulsion of aluminium strips from the bottom of a metal can after a contact with a charged object introduce charging by contact and movement of charge; when a charged object is only brought near to the can the observed effect is linked with the presence of (microscopic) entities into the neutral can; the process of induction offers an interpretation of the experience and is the starting point to explain the behaviour of a plastic bottle and of a foil electroscope. The activities involve insulators and conductors, to see the similarities in the process of charging, for a highlight of the global nature of electricity, and the different mobility in them, as responsible for the difference in time where electrical phenomena are involved.

Faraday cage: The change in distribution of charge on an flat aluminum sheet after its shaping as a cylinder and the induction produced by a charged bar inserted on a metal can leads students to acknowledge the distribution of charges on the outer surface of a conductor and the charge measurements made by a charge sensor (Pasco) and a Faraday cage.

The second part of our proposal aims to introduce potential as a new property needed to manage the transfer of charge, emerging from explorations designed to face the learning knots pointed out by the previous analysis of the subject content and of the learning difficulties. During the exploration of simple transfers of charge some features of the potential emerged, as its depending on variables specifically studied.

Moreover, the exploration leads students to observe the conservation of charge as a constraint of the process. A further step aims to give a meaning of potential as work needed for the transfer of charge. Then potential is linked to the electric field, that is explored.

The first exploration concerns the transfer of charge in rubbing: the objectives of measurements of charge on two objects rubbed together are to introduce students to the way of measurement proposed, and to develop the model of charge transferred from one object to the other while conserving it as explanation of the same quantity of charge of different kind, looking at the global system of both objects involved in rubbing.

The next step concerns the transfer of charge by contact. The measurements explore first the contact between a rubbed (charged) insulator and a neutral metallic sphere, showing a transfer by contact between insulator and metal; then, successive contacts of two metallic spheres, identical and not, in different starting situations are observed: (a) only one sphere charged, to study the transfer on a neutral metal, in equal or different quantities; (b) both spheres charged, to study the transfer between charged objects. The proposed sequence aims to create in the students a conflict situation when appears a transfer of charge from a little sphere to a big one, increasing the difference in charge on the spheres instead of decreasing it, as the usual model emerged from literature should predict. The measurements are easily explained if a new quantity is introduced that manages the transfer, "potential", depending from the charge on the spheres and from their size. The proposed explanation is summarized in Fig. 47.1. It is organized in steps as follows:

Step 1: After a contact of two equal spheres, one of which charged, half charges transfer: assuming a state of the charged sphere as referent for the condition of the charge configuration producing a transfer, after the contact both spheres are in the same state; it can be labeled by the charge on them.

Steps 2 and 3: A transfer is carried out in two pairs of spheres, each of them composed of one of the previously charged spheres (having the same charge and size)

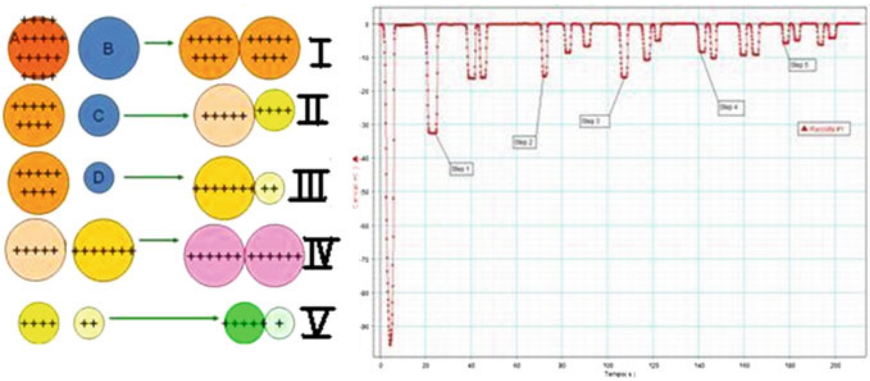

Fig. 47.1 Example of a measurement during the steps (*left*) for introducing the need of potential

and one smaller neutral sphere (of different size): the different amounts of charges on the smaller spheres are related to their different size, introducing a dependence of the state on the size of the objects; the amounts of charges on the two equal spheres are related to their state, as their size is the same. A hypothesis can be done that the greater amount of charge on them is related to a greater capability to transfer. The final state of each smaller sphere is the same of the big sphere it touched, so a comparison can be made also between the states of the two smaller spheres, showing in the smallest sphere a better capability for transfer than in the other little sphere.

Step 4: After a contact of the equal spheres with different amounts of charge, the amount of charges become the same on each sphere: the previous hypothesis is checked and the same final condition referred to the charge can be assumed also if both spheres are charged.

Step 5: After the contact of the two different spheres with different amounts of charge, ΔQ increases, according to the hypothesis that the sphere with a smaller amount of charge and a smaller size is in a state more favorable for the transfer than the other. The quantity related to the state of the spheres is named "potential" and it depends on both size and charge of the spheres. Each steps shows that in the transfer charge is conserved.

A meaning for the new quantity is provided with an exam of the charge transfer between two spheres linked by a paper strip, showing that charge is transferred also by an insulator, along a path, and then doing the same in different ways: by a person making a work on the charges, bringing them from one sphere to another by a little conductive disk attached to an insulated handle, or using a battery. This work is stored with the charge transferred and gives a measure of the capability of transfer of the charge. Bringing charge on a conductor (the sphere) requires increasing energy as the charge on it increases, and produces an increased capability of transfer in this charge. Measuring the charges on the involved objects (spheres and disk) during each step of the transfer, students can see that the disk does not discharge completely, and that the charge transferred diminishes with the increasing of the amount of charge (and its potential) on the sphere to charge. The charge transferred (and therefore the efficiency of the charging process) depends on the potential difference, as can be seen looking at the transfer between charged sphere and disk, according to the capability for the charge transfer, and the transfer stops when the potentials on the different conductors are the same.

A generator or battery is then introduced as a device able to charge a sphere at a fixed potential, 1, 2 or 3 kV with Pasco equipment; after charge measurements on the 3 different spheres used before, students observe that charges on each sphere are in the same ratio of its potential, establishing a relation between charge and potential, where capacitance, C, is introduced as the constant between the charge, Q, and the potential V, $Q = CV$; looking at the measurements on different spheres the dependence of capacitance from the size of the sphere (its radius, R) can be seen, $C = kR$; combining the two relations a formal expression for the previous qualitative observations can be stated, as $V = kQ/R$.

The process of charging a capacitor is examined in detail: it is introduced in the context of the previous experiences, and starts from their conclusions. It can be a starting point for exploring the space between its plates, to build the concept of field with one explorer moved and then filling the space in two or three dimensions with several little explorers as fragments of tea leaves in oil.

After the planning of the sequence we defined a main Research Question, asking if it is possible to build an educational proposal from middle/junior high school students and for teachers, starting from the macroscopic exploration of phenomena and using its power to interpret them, addressing subject and conceptual knots in electrostatics as regards potential and field too. We suppose that only a sequence coherent in the step by step conceptual outcomes could be a basis to link electrostatic and circuits. We designed a set of Research Questions to obtain an overall view. As concerns the transfer of charge by rubbing, and the objective of the measurements carried out, we state a first Research question:

RQ1: Do students recognize a transfer of charge and its conservation in exploring electrification by rubbing?
As concerns the transfer of charge by contact our Research Question takes into account the explanations of students:

RQ2: What are the spontaneous reasoning of students in explaining the transfer of charge? Do they take into account the conservation of charge?

RQ3: What changes produces the proposed sequence into the students reasoning about the transfer of charge? Did the reasoning involve only one object or take into account the system?

47.4 Data and Discussion

A one hour activity was carried out with 2 groups of middle school pupils, M1 and M2, focused on the measurements of charges on rubbed objects, after a brief discussion about the experiences of the first part of the path. The same focus was given in a path proposed in a last year class of high school, H1. In another class of the same level, H2, the whole proposal was carried out. We analyzed the worksheets related to the experience of measuring the charge on rubbed objects, and test in/out for the whole path in H2. The test proposed situations of contact of charged spheres, as in literature [10] asking for a prevision and an explanation about the final charge distribution.

After the experience of charging by rubbing, pupils were asked for an explanation for the unlike signs of the charges on the objects (QA) and for the equal magnitude of the two charges (QB). The answers take different directions in the two groups: a majority in M1 (20/30 pupils, 67 %) relates the systems condition with the measured values, tautologically, explaining QA: "because one (object) was positive and the other negative"; more than half of the group does not answer in QB, but 12/30 pupils (40 %) explain the same magnitude with the same process on the objects; "there was the same number of charges having suffered (the objects) the same process" or "because they were rubbed each other". The other group (M2) related the observed outcomes to the features of the systems: 26/28 pupils (93 %) for QA explain the different sign of charges with the different color of the objects: "the two disks had a different colour", and for QB explain the same amount of charge with the same shape: "are both disks, the disks are equal". In H1 we observe for QA in majority the same kind of answers of middle school pupils: 5/12 students answer as M1, 2/12 as M2 (referring to the different material of the disks); 3/12 students claim a process (microscopic) that involves charges: a separation of charge, "in rubbing, the opposite charges displaced on different disks"; a transfer, "there was a charge passage from a material to the other", a polarization. "the charges take an opposite orientation". For QB 4/12 students relate the systems condition with the measured values, tautologically ("the charges after the rubbing are equal"), 2/12 explain the same magnitude with the same process on the objects ("They were charged in the same way for the same time").

The outcomes from the test in/out of the class that carried out the whole proposal can be summarized referring to situation (a), where 2 equal spheres were charged before the contact with $+8\mu$C and $+2\mu$C. In test in, 50 % of pupils explain the final situation in terms of evolution of systems in different states towards a common state of equilibrium (process); 33 % explain the impossibility of transfer with a reasoning based on the Coulombian force. Analyzing the other situations, reasoning based on the idea of force is expressed in different situations and produces several images about the processes and the final charge distributions. Two kinds of process emerge in answers admitting a charge flow for equilibrium: a charge transfer from the more charged sphere to the other with neutralization of opposite charge, or a charge flow in both directions to reach the same configuration of charge on both spheres without a need of neutralization. After the activity, in situation (a) 100 % of students admit a transfer; forces are not cited in explanations; 66 % of explanations referred to a process of transfer: "The two spheres have the same dimension, so the transfer of charge will happen from the more charged sphere and there will be a re-distribution between the spheres leading them to equilibrium"; the others cite the final equilibrium state: "The sphere will reach the electrostatic equilibrium"; 4/19 students introduce the idea of potential as reference for the transfer.

As concerns our Research Questions, we conclude that:

RQ1: Pupils of middle and high school recognized that both objects charged by rubbing, but did not recognize a transfer and conservation of charge. They relate the same rubbing or the same shape of the objects with the same amount of charge, the difference in material with the difference in sign: pupils show a local reasoning, looking at the system as a set of separate systems; a process of transfer did not emerged. Moreover, the different material of the discs could be a cue of the need of a general rule managing the process, avoiding a different effect of the same rubbing on different materials. This did not emerge, also if the reasoning of high school students shows a implicit assumption of the charge conservation.

RQ2: High school students' reasoning for charge transfer grounds on the concept of force (Coulombian), or on a model of fluid. The processes involving this model are symmetrical (a transfer in both directions, a spreading of the common charge) or not: in this process the charge transfer happens according to the amount of charge. Conservation of charge is assumed implicitly, excluding the charge configurations where charge is not conserved.

RQ3: After the instruction, a new way to look at the situations is produced, where there is a referent for the final state of equilibrium, the potential, and it is taken as a criterion for the transfer. This new perspective implies to look at the system as a whole.

The different perspectives adopted by the students in observing a simple electrostatics phenomenology suggest the need to discuss these models also with teachers, during teacher education. The proposal could be further developed, to shift the concepts in the context of electrokinetics.

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