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Pupils' ideas exploration on metal electrical transport models in the informal context of an hands-on exhibit

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Abstract

A wide literature considers the problem of learning relative to the electrical circuits starting from different perspectives. A lot of work has be done as concern learning difficulties on developing systemic reasoning on functioning of electric circuits, on different aspects: 1) the conceptual differentiations of charge, current, voltage, energy, 2) establishing phenomenological relations between electrostatics and electrodynamics, 3) linking macro and micro level of description of processes. Different strategies are implemented in teaching/learning proposal on this last point and to produce a systemic vision and functional reasoning. Simulations are developed to provide micro level representation both of simple circuit functioning and of electrical transport phenomena in solids, but an exploration is lacking on spontaneous pupils' ideas about microscopic models of electrical conduction. Critical details and the spontaneous angles of attach to the topic are relevant in activating learning, therefore in simple situations with electric circuits, individual interviews are submitted according to a semi-structured protocol to 10 (N=11) and 13 (N=35) year old pupils of 3 different schools in the context of an hands-on exhibit, to gain competences in the representation perspective of pupils in their first approach to the models of electrical conduction in metals.

Keywords: Pupils' spontaneous mental models, electrical conduction in metals.

Resumen

Una amplia literatura considera el problema de aprender en relación con los circuitos eléctricos a partir de diferentes perspectivas. Un montón de trabajo ha estado realizado sobre las dificultades de aprender en el desarrollo de un razonamiento sistémico en el funcionamiento de los circuitos eléctricos, en diferentes aspectos: 1) la diferenciación conceptual de la carga, corriente, voltaje y energía, 2) el establecimiento de relaciones fenomenológicas entre la electrostática y la electrodinámica, 3) la union a nivel macro y micro de la descripción de los procesos. Diferentes estrategias se aplican en la propuesta de enseñanza / aprendizaje en este último punto y para producir una visión sistémica y el razonamiento funcional. Se han desarrollado simulaciones tanto a nivel micro para dar una representación del funcionamiento de los circuitos simples como tanto de los fenómenos de transporte eléctrico en los sólidos, sino falta una exploración en las ideas espontánea de los alumnos de los modelos microscópicos de conducción eléctrica. Los detalles criticos y los ángulos espontánea de unir a los temas son relevantes en la activación de aprendizaje, por lo tanto, en situaciones sencillas con los circuitos eléctricos se presentan entrevistas individuales de acuerdo a un protocolo semi-estructurado a los alumnos de 10 (N = 11) y 13 (N = 35) años de edad de 3 escuelas diferentes en el contexto de una exposición hands-on, para ganar competencias en la perspectiva de la representación de los alumnos en su primera aproximación a los modelos de conducción eléctrica en metales.

Palabras clave: Modelos mentales espontáneas de los alumnos, conducción eléctrica en metales.

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I. INTRODUCTION

A wide literature [1, 2, 3] is devoted to study pupils' understanding of electrical circuits by very different perspectives.

The functional perspective was been the first inquiry goal in simple circuits [4, 5] using bulbs as indicators. The learning difficulties emerged in this context concern: the role of closed circuit, the concept of electrical current and of voltage, the use of systemic reasoning instead of local and sequential reasoning. The circuits topology has been found [6, 7] a knot linked to recognizing equivalent circuit as describer of many loop circuit. These researches have pointed out the diffuse and persistent presence of students' spontaneous mental models about functioning of the electrical circuits that are hard to overcome for gain the scientific view [8, 9]. In connection with these researches, teaching/learning proposals have been experimented that help the students to develop systemic reasoning about circuit functioning [6, 10, 11, 12]. A direct active engagement of the students on a wide spectra of situations facing the topological knot [6, 7] appear to be a necessary condition to activate systemic analysis reasoning of the students on circuits functioning.

Eylon & Ganiel [13] find that the missing link between electrostatics and electrodynamics is the main reason of the students' lack of conceptual knowledge about electric circuits. In accord, Thacker, Ganiel & Boys [14] later find that students whose instruction include an emphasis on microscopic processes involved in the electric circuits functioning develop a better understanding not only of simple macroscopic phenomena but also of more complex phenomena as the transients ones. Tveita [15] uses untraditional teaching methods in dealing the kinetic particle model of electron gas for electrical conduction to students from grade 6 to grade 10. He supports the hypothesis that if a student understands the particle model then he is able to explain the circuits phenomena.

On the other hand, the teaching of this subject based on *Coordinated models*, ones that use linked micro-mechanisms and macro-representations of electricity, [16] produce students passive attitudes of storage the model with little reuse for purposes of interpretation. It is therefore necessary to activate the students effort of construct their own model for testing in several situations.

The need of microscopic models as interpretative instruments of the systems behavior [9] is been addressed by means of the offer of simulation tools; the most interesting are PhET Interactive Simulations [17] or Easy Java Simulations [18]. Showing current as moving electron spheres to directly counter the spontaneous model that current is consumed, but the physical proportions among electrons and lattice ions are not respected. However such simulations can help to show how macroscopic properties emerge from a microscopic model at the level of material individual constituent and their interactions.

The identification of physical quantities (charge, voltage, current, etc.) that account for the electrodynamics phenomena as well as the circuits functioning is a teaching/learning proposal coherent and rigorous [19], from which to develop a more complete interpretative framework also on the physical plane, based on the role of the electric field [20].

It remains an open question to construct a bridge between spontaneous microscopic models and physical quantities that describe the physical processes at the macroscopic level. As educational goal, explaining electrical transport properties of materials bridging structural characteristics with macroscopic electrical behavior, by means of dynamic microscopic model offers the opportunity to reasoning in terms of metaconcept in science.

It's well-known [21] that an approach based on the spontaneous angles of attack to specific contents starting from common sense is a necessary condition to activate the learning process. Therefore it is important to identify and explore the representations with which children relate the microscopic to the macroscopic world, in particular the spontaneous ideas about the interpretative aspects of the structural properties of material. And this is important for teacher too [22]. Research is needed on the naive representations of the relation between the microscopic process and the circuit behavior. Then in this paper we analyze: 1) Which microscopic models emerge spontaneously in pupils reasoning of electrical conduction phenomena and 2) The persistence and the reuse of same models on changing the geometric parameter of the wire or the circuit topology.

II. CONTEXT AND RESEARCH QUESTIONS

Cognitive Laboratory of Operative Exploration CLOE [23] has been chosen to promote pupils' active involvement in operative way. The protocol of CLOE is adapted to the scope of the present research, mainly as concern the pupils' spontaneous ideas exploration. The material used where those of the hands-on exhibit GEI (Games, Experiments, Ideas) [24] consisting in semi-structured parts to be connected in order to obtain different circuits. The currents in a circuit are analyzed in qualitative way through the brightness of explorer bulbs in the branches interested.

The presented study aim to give answer to the following research questions:

R1. What kind of microscopic model of dc electrical conduction in different materials is spontaneously evocate by the students?

R2. Which reasoning do the students use to relate their spontaneous microscopic models with the observed phenomena?

R3. How are their microscopic models used to explain the changes due to changes in structural parameters of a metallic conductor wire?

R4. How the microscopic model is employed to predict the current in different branches of more complex circuits?

III. SAMPLE AND METHODOLOGY

The sample consists of 10 (N=11) and 13 (N=35) year old pupils from 3 different schools of Udine country. The activities were carried out in April 2011 in the context of GEI 2011 exhibit and involved 11 pupils from one class of primary school (age 10) plus 17 and 18 pupils from two classes of secondary school (age 13) chosen among the visitors of GEI exhibit.

The activity is divided into two steps: F1 focus on the pupils construction of microscopic model; F2 related to the exploration on the way in which the model is eventually used to make predictions in new situations. In this second part the PEC strategy (prevision/experimentation/comparison cycle) [25] is used. The whole activity is audio-recorded.

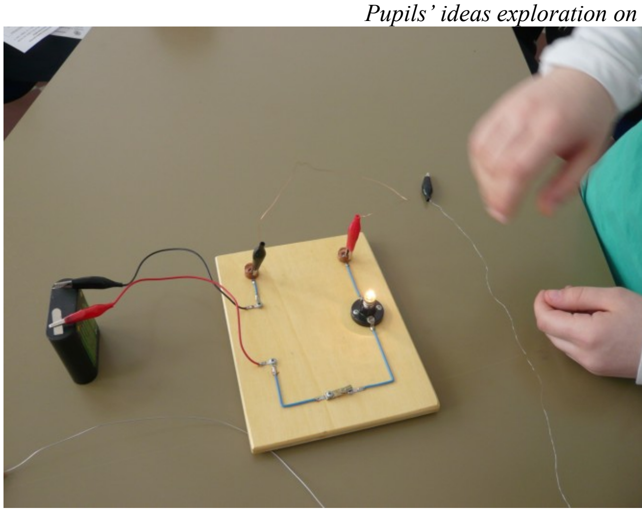


FIGURE 1. It is shown the simple circuit and the wires used in the first step of experiment.

Are available five wires. Three of different length (short, medium, long) and of same material and thickness; also the widest wire is of same material (constantan) that we for simplicity call iron; the last wire have same length and thickness of medium wire but it is made of copper. In order to evaluate the feasibility based on bulb brightness, measurements are performed, in absence of students, of: length l and diameter d of the wires; current I in the circuit with fixed battery; the relative power $(I/I_{max})^2$; the relative brightness directly by light sensor (Table I).

TABLE I. Bulb brightness as a function of the wire.

Wire	l (cm)	d (mm)	I (A)	I^2/I_{max}^2	rel. br.
Short	18	0.2	0.16	71%	90%
Medium	38	0.2	0.13	47%	39%
Long	57	0.2	0.11	34%	19%
Widest	38	1.1	0.19	100%	100%
Copper	38	0.2	0.19	100%	100%

The data in the last column of the table confirm our hypothesis that the brightness of the bulb is evaluable as I^2R_B with the bulb resistance R_B unknown but independent by the current, and shows that it is no difficult to see the changing of the bulb brightness after substituting the wire.

At the beginning of the step F1 the pupils are free in open environment to operate in individual mode in order to light the bulb of a simple circuit (Fig. 1). On the table are available: their pens or pencils, little sticks of different matter (copper, aluminium, plastic), a lead of well tempered pencil and the wires. Are proposed questions: to explore ideas on the role of the different circuit components (D1, D2, D3); to inquire which microscopic model is used to explain the bulb brightness changing when the circuit is closed with different materials (D4, D5, D6); to individuate the model and the reasoning applied to explain the bulb brightness change on changing the geometric parameter of the wire (D7, D8).

The 8 situations showed in Table II are divided into pairs S1, S2, S3, S4. The elements of a pair (except for S1) differ in the variation of a single parameter related to work resistance, while other parameters remain unchanged.

TABLE II. Situations of the first step.

	parameter	bulb	
S1	Switch	lighted up (on)	light out (off)
S2	Wire material	very bright (copper)	dim light (iron)
S3	Wire length	very bright (short wire)	dim light (long wire)
S4	Wire width	very bright (thick wire)	dim light (thin wire)

Each pupil is provided with a sheet divided into 8 grid. The pupil task is to draw and to illustrate, following the request also written on both pages of the sheet: *Imagine to get so small that you can enter into the wire. Try to think how the wire is around you. Draw how you represent the inside of the wire.*

In the second step F2 three different circuits are observed: a circuit that includes a switch, a bulb, a battery and a variable resistor (Fig. 2); a circuit that includes a battery, a switch and three light bulbs in parallel (Fig. 3); a circuit that includes a battery, a switch and three light bulbs in series (Fig. 4). Questions are proposed in order to inquire the pupils reasoning about: the bulb brightness change on changing the circuit length (D9); the variation of bulbs brightness on unscrewing one bulb in the parallel circuit (D10); the analogue situation in the series circuit and the comparison with the brightness of bulb in the first simple circuit (D11).

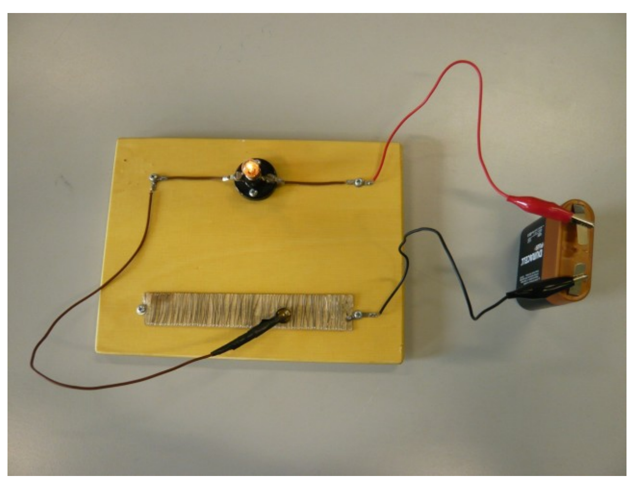


FIGURE 2. Circuit with variable resistor.

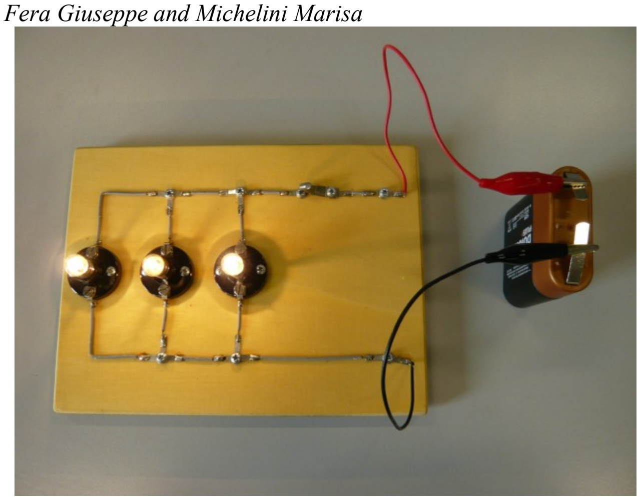


FIGURE 3. Circuit with bulbs in parallel.

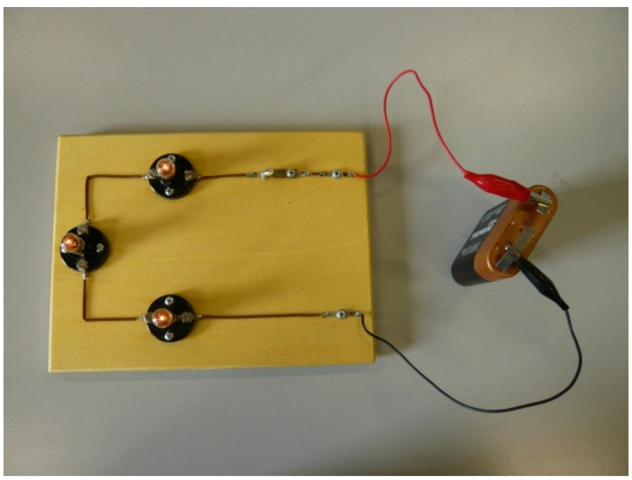


FIGURE 4. Circuit with bulbs in series.

IV. DATA ANALYSIS

The data analysis is carried out on the qualitative level classifying in categories the single oral answers to the interview and the sketches. The answers by 10 years old students (G10) are distinguished by those of 13 (G13) years old.

A. Interview

In the following the individual answers are grouped according the meanings; when ambiguous or emblematic answer is given, we report the whole sentence.

D1. What is the role of the battery?
G10) A) To supply energy to wires so that it arrives to the bulb (11).
G13) A) no answer (16). It generates: B) current (9), C) electrons (5), D) electricity (3), E) energy (1) *To supply electrons able to transform kinetic energy into luminous energy.*

D2. What is the role of the wires?
G10) A) To transfer energy possibly in different ways if the colour of the wires ends is different (9) refuted: *Colour has nothing to do, it is the material (of wires) which transmits energy* even operationally by two kids B) who exchange the red and black ends, showing that the bulb turns on lights up in the same way (2).
G13) A) The wire is needed in order to allow the flow of electron to pass (35)

D3. What is the role of the switch?
G10) A) It closes energy when the latter flows (6), B) It transmits energy to the other blue wire that continues on the other side (5).
G13) A) To close the circuit (35).

D4. Closing the circuit, the bulb lights up. What do you think is different within the wire, when the bulb lights?
G10) A) Energy is located in some regions (9) or B) is transferred: *Particles transmit energy to each other through electric pulses* (2). Energy is located: A1) within the wires (4), A2) around the wires (3), A3) in the air (2). In order to justify A1 they claim that: *The wires give a push to energy so that it can arrive to the bulb.* In order to justify A2 they claim that *The wires attract energy.* In category A1 the energy within the wires is imagined as a set of particles: *When the bulb lights up, the energy particles pass; when it is turned off, nothing passes, there are no particles* says Sergio as if the particles of energy were photons. *The particles are microscopic and move very fast* says Daniele.
G13) A) The electrons move among the atoms (20): *The electrons make a slalom between the atoms of the wire* and *If there is more space between the atoms of the metal, the electrons pass more, otherwise they pass less*. B) No answer (11), C) The wire is empty (4).

D5. A copper wire and an iron wire with the same length and section are used to close the circuit. How do you explain that the luminosity of the bulb is different? In the answer, say what do you think is different within the wires.
G10) A) the speed of energy (3) *iron does not allow energy to pass as fast*, B) the number of particles that transmit energy (3) *copper has more particles that transmit it*; C) no answer (3) D) the compactness of the material (2) *iron is more compact.*
G13) A) the number of atoms (20) *The number of atoms is different*, B) the interspace (8) *In copper, there is more space between an atom and another*, C) the number of electrons (7) *Less electrons pass in the iron wire.*

D6. A plastic, copper, or aluminium stick, a wood pencil, and a graphite pencil lead, are used to close the circuit. How do you explain the different luminosity of the bulb?
G10) There is a difference in: A) energy dispersion (5) *Wood makes energy disperse because it is not a conductor,* B) energy absorption (3) *Wood absorbs,* C) no answer (2)

D) the particle structure (1) *Wood has no particles, when iron was built particles have been added.*
G13) The material differs in: A) its ability to transmit electrons (14) *Conductor is the material that is able to transmit electrons*; B) the number of electrons (9) *In wood there are few electrons* C) the electrons freedom (8) *In iron, the electrons can move, in plastic they cannot*; D) the mechanism by which electrons move: going around/jumping (3) *In the metal, the electron go around atoms and from an atom to another*; E) the order of atoms and the related difficulty for electrons to pass (1) *In plastic, the atoms are in a mess, so it is harder for the electrons to pass, in metal the atoms are laid orderly*

D7 Copper wires of different length and equal section are used to close the circuit.

D7a. How do you expect the bulb luminosity will be affected?
G10) With the short wire, the bulb luminosity will be greater (11).
G13) Increasing the length of the wire, the current decreases (35).

D7b. Let us try. What do we observe? How do you explain that increasing the length of the wire the luminosity of the bulb decreases?
G10): Because the short wire has less dispersion: *The short wire retains more energy* or *Since it has a little path it disperses less the energy* (11).
G13) In the longer wire: A) the energy/the electrons find more obstacles (24) *The slalom which electrons must make is greater in the long wire* (16) *Energy disperses in the long wire because it finds more obstacles* (8) B) there is a greater dispersion of particles/energy (11) *The longer the path, the more electrons are dispersed in the material* (4) *Energy is dispersed in the wires that heats up* (3). C) No answer (3) D) There is more interaction between particles (1) *In the longer wire there are more atoms that attract electrons*.

D8. Iron wires of different section and the same length are used to close the circuit.

D8a. How do you expect the bulb luminosity will change?
G10) A) the luminosity will be larger for the thicker wire (9) B) the luminosity will be larger for the thinner wire (2) *In the small wire current there is less dispersion of the current.*
G13) A) the luminosity will be larger for the thick wire (35) *The smaller wire allows less electrons to pass, like a thin pipe allows little water to pass.*

D8b. Let us try. What do we observe? How do you explain that increasing the section the bulb luminosity increases?
G10) A) the particles (7) or B) the energy (4) move like a flow of people or traffic *A narrow street allows less cars at a time to pass* o *Because in the large wire flows more energy at a time.*
G13) A) Particles move like water in pipes (21), B) The quantity of electrons that pass in the little wire is smaller (7), C) In the big wire the space available is larger (7) *In the bigger one there are more atoms but there is more room.*

D9. How do you explain that the bulb luminosity varies moving the knob?
G10) The bulb luminosity depends on: A) the distance from the battery (10) *More luminous when the source of energy is closer* B) The folding of the wire *If the wire is folded, the current cannot pass freely* (1).
G13) The bulb luminosity depends on: A) the length of the wire, hence on its resistance (20), B) the dispersion of electrons (8) *Electrons must travel farther and disperse*, C) no answer (7).

D10a. How do you expect the luminosity of bulbs in parallel will be?
G10) A) The farthest from the battery shines less because less energy arrives (7), B) They all shine in the same way, but less than before because the battery powers three bulbs (4).
G13) A) The closer to the battery will be shiniest (32), B) They all light in the same way (3).

D10b. How do you explain that the bulbs in parallel have the same luminosity?
G10) A) by the distribution of energy in the circuit (5) *Energy divides equally between the three bulbs*, B) by the length of the path of energy *The path of energy has the same length*, C) no answer (2).
G13) A) By the distribution of current in the circuit (21) *There is an equal flux of current in each bulb,* B) Because wires are parallel (13), C) By the principle of communicating vessels. (1)

D10c. How do you expect the luminosity of bulbs in parallel will change if we unscrew one of them?
G10) A) All the other will turn off (11).
G13) A) Those that are farther from the battery will increase their luminosity, because the battery will give them the energy that it cannot give any longer to the other bulb (18), B) the luminosity will remain the same(17).

D10d. Having unscrewed one of the bulbs. How do you explain that the other bulbs keep the same luminosity?
G10) A) Once unscrewed, the energy passes through the other wires (8), B) no answer (3).
G13) By the invariance of electric voltage (4) *The voltage in the battery remains the same*, B) no answer (31).

D11a. How do you expect the luminosity of bulbs in series will be?
G10) A) The closest is more luminous because energy disperses (9), B) no answer (2).
G13) A) No answer (22) B) The closest shines more (12) C) It depends on how the electrons go (1).

D11b. How do you explain that bulbs in series have the same luminosity?

G10) No answer (11).

G13) A) No answer (31), B) Because the current is the same (3), C) As it happens at home, all bulbs light up in the same way (1).

D11c. How do you explain that bulbs in series have a smaller luminosity than the bulb in the elementary circuit?

G10) A) Because the battery is almost exhausted (7), operationally refuted by a kid who connects the battery to another circuit, showing that it is charged; B) no answer (4).

G13) A) no answer (18), B) by the distribution of current in the circuit (7) *As in the freeway there are three parallel lanes, here there is a queue*, C) by the topology of the circuit (6) *There is a single wire, before the bulbs had a wire each*, by the different voltage at the bulbs ends (2) *They do not receive all the same volt.*

D11d. How do you expect the bulbs luminosity to change when one is unscrewed?

G10) A) unscrewing one of the bulbs in series, all the other turn off (6), B) It depends on which one we unscrew (4), C) no answer (1).

G13) A) The luminosity of the other two increases (13), B) As in the case of bulbs in parallel, the luminosity of the others remains the same (12) C) no answer (10).

D11e. Having unscrewed a bulb. How do you explain that the other bulbs turn off?

G10) It depends on: A) the way the bulbs are connected (10) *Because they are all connected*, B) how the energy flows (1) *Energy does not pass any longer.*

G13) A) no answer (31) B) the unscrewed bulb behaves like an open switch (4) as if the bulbs were switches.

A typical lack of active participation of the children with respect to the pupils is systematic in the interviews; in other research CLOE was achieved a lively participation by implementing role-playing [26].

B. Sketches

The request is to represent the interior of the wire in the pairs of situations S1-S4.

S1) Closed and open circuit (Fig. 1)

G10) When the bulb is on, a sort of activation of the wire is represented (Tab. III) through a two kind of different symbol inside (6) and outside (5) the wire by means of continue or discrete elements. The types of symbols used are: A) sinusoidal or zig-zag bundles of lines (4), B) small circles or crosses, or short dashed lines (3), C) bundles of lines parallel to the axis of the wire (2), D) combination of A and B (1). The children used the same symbols to represent the change in the wire when the bulb is off, decreasing density of elements (3). There are also symbols related to the type B (5) or pictures in which the wire remains empty inside (2).

G13) One can find three main representations (Tab. IV) of the interior of the wire using: A) dense/rare (7), B) movable/fixed (5), C) presence/absence (3) of elements as small circles or crosses. A group represents the circuit rather than the inside, stating the connection mostly with D) a ring (12); in 3 cases the connection of the circuit is represented with a pipe E) difficult to classify (8). The ways of representing the interior of the wire are different: it's represented either a section (6) or a zoom of a piece (4) of the wire.

S2) Iron wire and copper wire of equal length and width

G10) The copper wire interior is described using the same types of pictures described above: A) (6), B) (2), C) most children use rarefaction again to represent the wire interior when the copper one is substituted by those of iron (10). A change of symbol is sometimes used to show the different material of wire.

G13) The representations of the interior of the wire contain: A) far/near (6), B) dense/rare (5), C) large/small (1) obstacles. As concerned for the other drawings: D) not classified (17) E) representation of the circuit outside rather than inside (6). A group of 11 students draws with different symbols the fixed (obstacles) and mobile elements within the wire; 4 of them show the trajectories of the moving parts through a pattern which reminds to the percolation (Tab. IVb).

S3) Short and long copper wire

G10) Children represent the inside of the short wire using types A) (5), B) (2), C) (2). A new symbol (small lightning, Tab. IIIc) is introduced (1). The rarefaction sketch, and in one case the concentration (1) of the symbols, is used once again to represent the change in the interior of the wire when it becomes longer (5). In the other cases, the interior of the wire is left empty (2) or there is an outdoor activation (2).

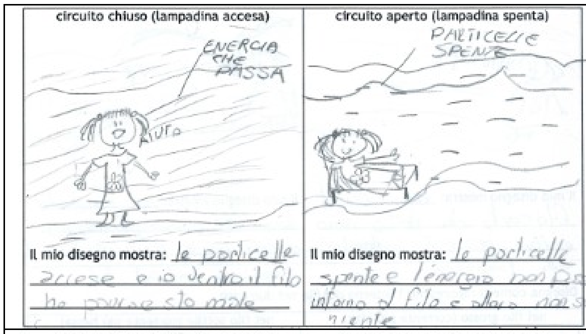
G13) We can see two representations of the wire interior: A) dense/rare obstacles (14), B) slower/faster moving elements (1). As for the other drawings: C) not classified (11) D) representation of the circuit from outside rather than from inside (9). One student reuses the percolation (1).

S4) Thin and thick iron wire

G10) The interior of the thick wire is described by reusing symbols A) (7), C) (3), small lightning (1). To represent the inside of the thin wire all children reuse rarefaction (11)

G13) There are essentially two representations of the interior of the wire: A) dense/rare obstacles (12); B) in movement present/absent (1) dense/rare elements (11). As for the other sketches, we can find D) not classified (8) E) representation of the circuit rather than of its interior (3). A group of students reuses percolation (5).

TABLE III. Example of sketches of G10 students.



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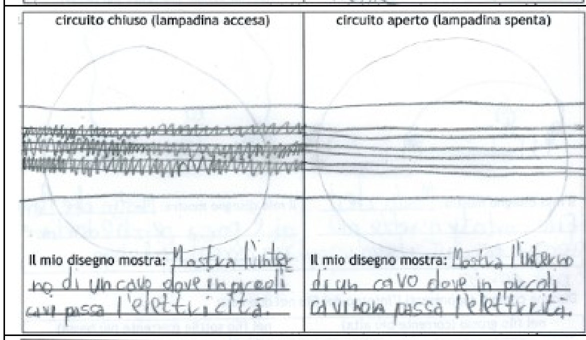

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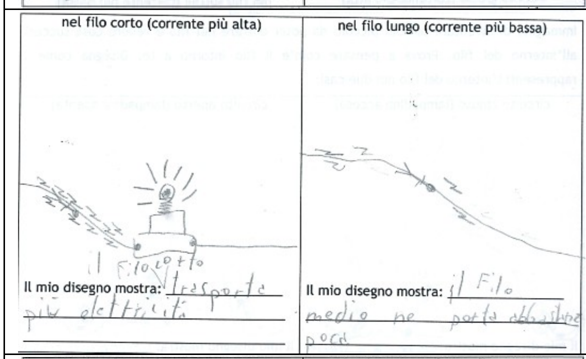

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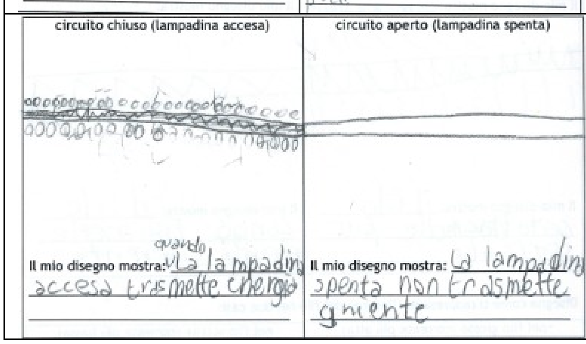

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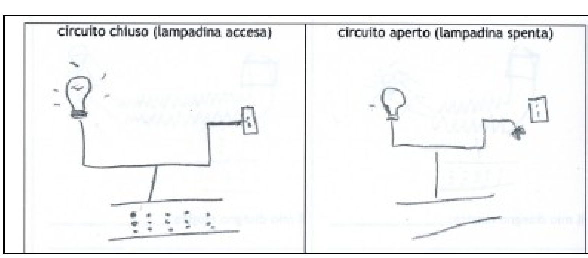
TABLE IV. Example of sketches of G13 students.



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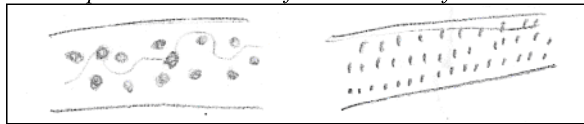

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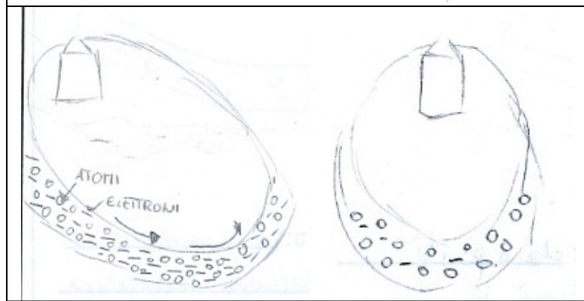

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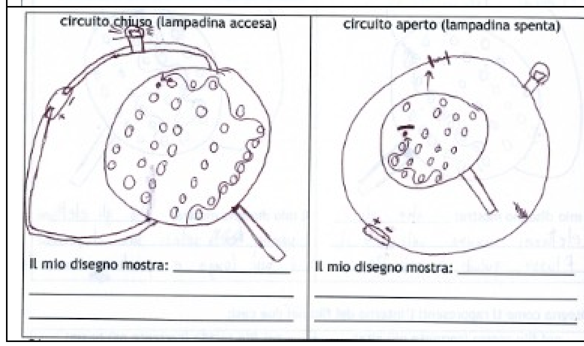

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V. DISCUSSION

In the first step of the intervention experiment, students use objects of different material to close a circuit with a battery and a bulb. From data D1, D2, D3 emerge what follows. The battery is seen by the children (G10) as a source of energy while the pupils (G13) look it as a generator of "electricity" or even electrons. The wire role of transferring something is clear to everyone but is different what one believe to be transferred: energy or "electricity"/electrons. The role of the switch is for all to run or stop what is flowing in the wires. The identification of the battery as energy source is a general point of view. Two children consider the terminals of the circuit as magnetic poles, confusing the electric phenomenon with magnetic ones as documented in other studies [27]. In drawings the correlated representation of the internal part of the wire is associated for the children to an energy state or to an energy transmission process. Small electrical discharges and lightning are draw as a reminiscence of the electrification represented in a cartoon. The energy inside the wire is imagined as a set of microscopic particles that go very fast (D4). Pupils drawn and describe the conduction in wires with a microscopic view of particles/electrons moving among the atoms (not much more big) located in the wire as obstacles. By closing the circuit with a copper or iron wire with equal section and length (D5), the majority of the children use reasoning that relate the difference in brightness of the bulb to the size or the speed of the particles that transmit energy in the material or to the compactness of the material. The pupils reuse the model of the atoms as obstacles in two different ways: By number/interspaces of atoms and/or by number of electrons.

The possibility of closing the circuit with different objects (D6) produces five hypotheses on the dependence of the bulb brightness: 1) The peculiar characteristic of the material in facilitating the electrons transmission, 2) The increasing/decreasing number of electrons, 3) The freedom of the electrons, 4) The electrons mobility, 5) The order of the atoms and the relative difficulty of electrons to move through the atom structure (the first idea of resistivity). The decrease of bulb brightness in longer wire (D7) is due for all the children to a dispersion of energy. The pupils reuse the atoms as obstacles model to explain the same phenomenon.

When the children close the circuit with wires of different section (D8) they motivate different brightness of the bulb using an analogy between the movement of microscopic particles and traffic.

In the second step of the intervention experiment, students use three new circuits, one with a variable resistance, another with three bulbs in parallel and the last with three bulbs in series. To explain because the brightness of the bulb varies by moving the knob (D9) the children reuse the idea of the dispersion of the energy linking the brightness of the bulb to the proximity of the battery while the pupils reuse the model of the dispersion of particles. These ideas are reused by the majority of children and pupils also to explain the behavior of the parallel circuit (D10). Few pupils use the concept of invariant voltage on the heads of users connected in parallel. The brightness of the light bulbs in the series circuit (D11) is in contrast with students' expectations and therefore no child provides explanations.

In the interviews, the different conceptual referents for children and pupils as concern electricity in wires of working circuits are consolidated in energy and electron flux for children and pupils respectively, including in some cases the idea that in insulating materials such as wood electrons do not are present.

The children draw the personal idea of the inside of the wire using symbols rarefaction (S1-S4) to represent the change into the wire indicated by the lower brightness of the bulb. About half (19/35) of the pupils reproduce the circuit component simply as lines or pipes without representing the wire inside: a need to distinguish between the circuit diagram and drawing appear evident. When they represent the state of motion of the particles inside the wire, some pupils recall the idea of percolation (S2). In very few cases (3) the micro world is the reproduction in small dimension of the macroscopic reality. Some students (8) - both 10 and 13 years old - represent by means of iconographic symbols (dots, stars, dashes, …) their models on functional aspects of simple resistive circuits. These models suffer the same limits of many simulations of the electric current in a wire, where the relative distances, dimensions and speeds of the particles are not respected. Nevertheless these models are consistently used for interpreting the observed phenomena with reasoning based on cause-effect relationships.

Research question R1

G10) The indefinite idea of energy is the basis of the children representation and establishes the electric current. Three models emerge: the energy is carried by the wire; the particles carry the energy or energy particles are into the wire, represented in the drawings with growing density according to the bulb brightness.

G13) Most of the pupils correlates the difference in brightness of the bulb to the microscopic characteristics of the material that closes the circuit. Even in the drawings there is a microscopic justification of conduction: the model is made up of small objects in motion among larger objects, which are obstacles. The students predict that the brightness of the bulb decreases if the obstacles are more numerous or neared or, in some cases, greatest.

Research question R2

G10) Most of the children uses reasoning that correlate the difference in brightness of the bulb to the number, speed of energy particles or compactness of the material. In the drawings the children represent a rarefaction of the symbols linked to the situation in which the brightness of the bulb is weaker. A child brings this idea to the extreme by saying (D4) that when the bulb is off the particles of energy are absent.

G13) The majority of pupils uses reasoning that link the difference between the state in which the bulb is on and the state in which the bulb is off to the difference of the dynamic state of microscopic particles that they call electrons and that in the drawings run along percolating paths among regular structures changing with the different material. In the drawings we find the representation of the variation of the microscopic structural characteristics of the material to justify the observed phenomena.

Research question R3

G10) The children explain the decrease in brightness of the bulb, when the wire length grows, with the dispersion in the wire of the energy particles. The analogue decreasing of brightness in the case of wire section decrease is justified by analogies with the traffic of peoples or cars, or with the fluids slide.

G13) In the reasoning of the pupils to explain the variation in the brightness of the bulb, corresponding to the variation of the geometric parameters of the wire, are used two microscopic models: an obstacles model or a dispersion model, similar to the previous but referred to the electrons. In the first, the passage of electrons in the wire is constrained in different ways depending on the microscopic structure: into the long wire there are more obstacles, into the widest wire the space among the obstacles is reduced, in the iron wire obstacles are larger. In the other model, less articulate, the dispersion of electrons in the wire accounts for the decrease in brightness of the bulb.

Research question R4

During the discussion about series and parallel circuits, the microscopic model introduced by themselves is given up by almost all the students (11/11 children and 31/35 pupils).

The model of consumption [8] is prevalent, even if it is contradict by phenomena.

G10) The children apply the model of consumption to their reference entity: the energy.

G13) One pupil use the principle of communicating vessels to explain the same brightness of parallel bulbs (D10): the energy is distributed among the bulbs in the same way as the water reaches the same level in the vessels. The analogy with the traffic road can correctly interpret the decrease in brightness of the bulbs in series in comparison with the ones in parallel (D11), because, with the same battery voltage, the current in the parallel circuit has more available roads than in the series circuit and is, therefore, greater.

VI. CONCLUSIONS

The children (G10) evoke a conceptual referent called energy (see R1) to account for electrical process in a consistent way, without mentioning charge. The referent for interpretation (established as energy) is a synthesis of state and process responsible. This confirms that the children never produce a description without a related interpretation [28]. In the same time this result confirm: 1) The attitude of children to focus the attention to the processes, 2) The need to relate the idea of moving entities with the charge in the matter. Although the energy that they are talking about remains an undefined entity, it still has the characteristics of an almost physical property that gradually acquires the features of an interpretative framework [29] with increasing amplitude. It is applied consistently to interpret the phenomena in different contexts and allows children to overcome the local contextual vision. According to Guile [30] this seems to be a necessary step to overcome the common sense vision [31].

The pupils (G13) use atoms and electrons as referent entities, building a consistent representation of internal structure and conduction process in terms of mechanical interactions between particles. The Psillos' [19] critics results compared to expectations as concern the propaedeutic role of physical quantities (voltage, current, charge, etc.) in approaching microscopic models, appear to be due to the need of a microscopic qualitative description/representation to approach the meaning of physics quantities and its interpretation. The representation they provide to interpret phenomena in terms of the structure and role of microscopic entities (see R2 and R3) is often surprisingly close to the physic perspective and creates the micro-macro link addressed in literature [13].

The reasoning of the students are not naturally linked to the microscopic level (see R4), but the reflection on the microscopic level helps in overcoming local reasoning. The references to the microscopic elements and processes are a resource for learners.

The reference to analogies (see D8) is indicator of the kind of reasoning useful to students to construct meaning, according to Fuchs [32], on the basis of similarities among different fields of physics.

The reasoning produced by students show an important characteristic: the attribution of the change in the behavior of the system to change of its microscopic properties as in a causal reasoning. While the tendency to avoid causality seems to have become dominant in science and philosophy, research in science education [33] has shown the strong presence in common reasoning of causal explanations, often conceived as a 'mechanism' accounting for physical processes.

The microscopic models have two roles: on one hand they provide a sound interpretation of phenomena in accord with scientific ideas, on the other hand they are a potential learning tool that children explicit, elaborate and share.

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