Magnetic Field Nature and Magnetic Flux Changes in Building Formal Thinking at Secondary School Level

Marisa Michelini, Research Unit in Physics Education of the University of Udine, Italy
Stefano Vercellati, Research Unit in Physics Education of the University of Udine, Italy

Abstract

The importance of the electromagnetism as topic itself and educational framework in which learn how to master multivariable abstract entities require the development of organic learning path for high school students. An empirical research done in the framework of a designed based research was performed in three different types of high schools to look at the reasoning that an organic learning path constructed on the formal construction of abstract entities promote in the students when the idea of the flux tubes representation is introduced as the key element in the interpretation of the magnetic field representation. The learning path, designed with an inquired based approach, provide to students the environment in which experimentally explore physical quantities constructing formal entities able to represent their properties. Then, the providing of challenging context, as the explanation of the processes of electromagnetic induction, allows to investigate how students validate and/or extend their interpretative model based on the constructed formal entities.

Introduction

Electromagnetism is one of the main topic addressed in the last years of the high schools and has an intrinsic importance in the understanding of several everyday phenomena. Research literature widely addressed the main learning knots related to this topic: the field representation (Guisasola et all, 1999), the field as a superposition (Viennot & Rainson, 1992), the relation between magnetic field and electric currents and the nature of field itself (Thong and Gunstone, 2008), the sources of field and the role of relative motion in the electromagnetic induction (Maloney et all, 2001) and the identification of the versus of the induced magnetic field (Bagno & Eylon, 1997) but there is a lack of proposals of organic learning path that cover all of them.

A first attempt to face this issue was proposed by Bradamante et al. (2005) using the field lines of the magnetic field as conceptual referent for the magnetic field representation. Looking at this particular angle of attach, in the framework of a Design Based Research, an organic curricular proposal was developed providing to students a specific learning path that, using inquired based tutorials, overcome the intrinsic qualitative nature of the field lines representation proposing the operative construction of the flux tubes as the way to construct the key conceptual referent for the exploration of the electromagnetic phenomena. In this approach, the idea of flux is constructed not only on a formal level but also on the conceptual plane, becoming so an operative conceptual referent which changes over time produce the phenomena of electromagnetic induction.

In particular, to investigate the students' reasoning promoted by the use of this learning path, the following aspects were addressed: How did the students construct the idea of field so that it could become an organic entity of reference (RQ1); When and how the concept of field become a conceptual referent in students' reasoning (RQ2); What is the role of the experimental exploration in building formal interpretative models of the electromagnetic induction (RQ3).

Methods

In the framework of a co-planning work to promote the innovation of the teaching strategies in the Italian high school, the experimentation of the learning path was carried out by a researcher in three high school classrooms at the presence of the school teachers. All the classes involved are grade 13th (students are mainly 18 years old) and are selected from different types of schools to test the portability of the learning path: one classical lyceum, one linguistic lyceum and one scientific technological lyceum. The experimentations were held in the schools in accordance with the standard time table of the involved classes using a total amount of 12 hours of lessons.

The proposed learning path was structured by means of a context related approach in which particular experimental situations are proposed as starting points of phenomenological investigations in the framework of a gradual grow of the level of formalization for the interpretative quantities adopted. The whole summary of the inquired learning based tutorial and the learning path are reported in detail in Appendix A. In this paragraph will be discussed the steps of the learning path exploiting the rational on it takes grounds.

The learning path begins with very simple situations presented as introductory activities aimed to recall student's everyday knowledge as regards the exploration of the simpler magnetostatic interaction between objects. In particular, a box full of everyday objects of different types is proposed to the students and was asked them to individuate the magnets in the box, describe the different type of interaction the they experiencing between the objects of the box and categorize the object by the types of interactions (activities 1-4 – Appendix A).

During these activities, as during the other ones proposed among the learning path, individual and group works are alternated to share and compare the findings inside the class.

Then (activities 5-10 – Appendix A), the compass is introduced as an explorer of a magnetic propriety of the space in one point that had to be explored and defined. In particular, the interaction between magnets are explored observing the rotations induced by the magnetic interaction and the analogy between the behaviors of the hanging magnet and the compass.

Even if the role of the representations was inserted already in a marginal way in the first ten steps of the learning path, in the eleventh it became crucial and is strictly related to the development of the formal representation of the physical entities involved (activity 11 – Appendix A). In particular in Activity 11.c, the students provide spontaneously a first representation of the magnetic properties of the space in one point. Their early representations are in all of the cases categorizable as a pictorial or a stylized representation of the compass needle representing or not the orientation of the needle. These will be the ground on which construct the vectorial nature of the magnetic field starting from this spontaneous versorial one.

But first, the representation by means field lines is presented to pupils overlapping the field lines representation to their versorial representation and discussing the validity and the pro and contra of both ones (Activity 11.d-12 – Appendix A).

In activity 13 was addressed in particular the limits of the versorial representation highlighting experimentally how this first formal representation is not able to describe all the characteristics of the magnetic field highlighting the need of introducing a way to represents also the intensity of this property. Highlighted an solved this issue of the versorial representation, the same problematic will be raised as concern the field line representation and in particular observing that in a simple field lines representation there is not a quantitative way to have information as concern the intensity of the magnetic field even if to try to correlate the distance (57%) or the density (29%) of the line with the intensity of the field – the idea that the intensity of the magnetic field is constant along a line was proposed only by few students (3%).

Following this shared expected spontaneous (and not correct) prevision, during activity 16, pupils are encouraged to validate their prevision and measure the value of the flux of the magnetic field between two field lines relating it to the height of the stripes bounded by the two lines. Then, looking that this correlation does not fit directly, after a discussion on the tridimensional structure of the magnetic field, they re-do the experiment looking for a correlation between the intensity of the magnetic field in one point and the area of the section of the tube constructed on the stripe bounded by the line in this point.

What emerge from this exploration is that there is an inverse proportionality between the value of the intensity of the magnetic field and the section of the tube. It means that the product between these two quantity had a constant value for each tube, but the value of this constant varies from tube to tube. It means that exist one way to relate the intensity with the section (and then the height) of a tube with the intensity, but the factor of correlation is not the same for all the tubes.

In this so is necessary a renormalization of the line to have the same value of the constant for each tube and so connecting equal height of the tube to equal intensity of the magnetic field.

In this way is possible to insert in the field line representation a metric that allow students to do quantitative forecast on the structure of the field around the magnet and in the same time, being the constant along the tube, the flux of the magnetic field, it is possible to correlate quantitatively the number of tubes crossing a surface to the flux of the magnetic field trough a surface or a circuit.

Then the learning path proceed with the explorations and analysis of different sources of magnetic field (Activities 17 and 18) and the exploration of the Lorentz force (Activity 19). At least, the phenomena of the electromagnetic induction is presented as an experimental exploration in which students had first to freely explore qualitatively the phenomenology individuating the main parameter that had a role in it (Activity 20) and then study the phenomena in and explorative way (Activities 21 and 22).

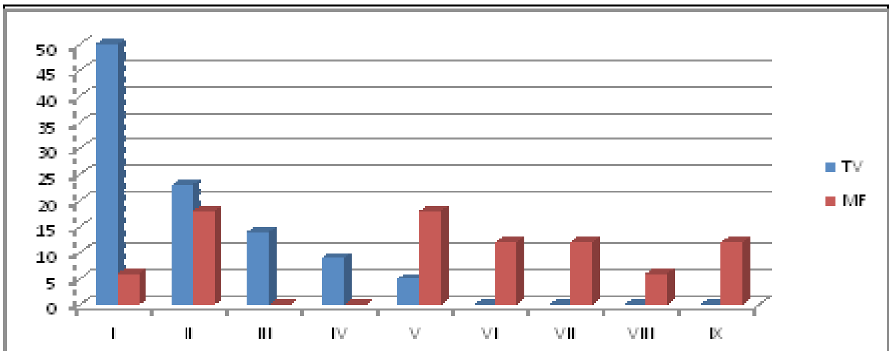
Data and findings

Data were collected from the students' writings on the inquired based personal worksheets proposed and from the audio recording of the argumentative discussions. Here will be reported and discussed only the data concerning the particular steps of the learning path that are related to the research questions took into account in the introduction.

For each question the students answers are categorized and grouped in categories token in accordance with the main categories highlighted in literature for analogues questions and in new categories that emerged from the grouping of the data in the framework of a phenomenographic analysis of the students' answers. In particular as concern the early phase of exploration the spectra of the possible answer is quite spread and different from class to class.

For instance in the following graph (Figure 1) are represented the distribution of the earlier representation used by the students in Activity 11 to represents the property of the magnetic property of the space.

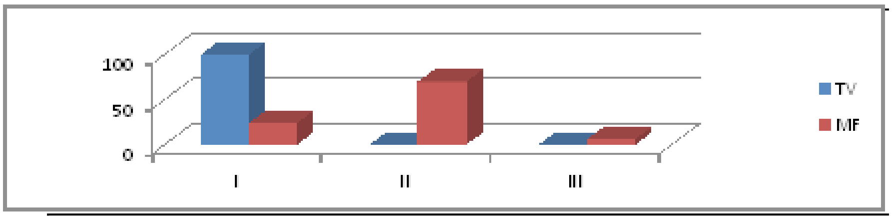
Looking at the results of the MF and the TV classes (a classical lyceum and a scientific lyceum respectively), the distribution of the data are manifestly different and they overlap only on few mainly minority categories. In particular the MF students seems to use spontaneously more formal terms related to their scientific instruction, while the TV students proposed more often iconography representations of the needle.



I	with a segment (TV 50%, MF 6%)
II	with an oriented segment / arrow (TV 23%, MF 18%)
III	with an oriented line (TV 14%, MF 0%)
IV	with a segment with 2 poles (TV 9%, MF 0%)
V	with a line (TV 5%, MF 18%)
VI	with an angle (TV 0%, MF 12%)
VII	with a mathematic formula (TV 0%, MF 12%)
VIII	with a vector (TV 0%, MF 6%)
IX	NR (TV 0%, MF 12%)

Figure 1. Distribution of the earlier representation used by the students in Activity 11

This also persist after the performing of the activity 13 in which, even if almost all the students recognize the necessity to use a vector as formal entity, the justification that arise from the discussion is quite different between the two classes (Figure 2).

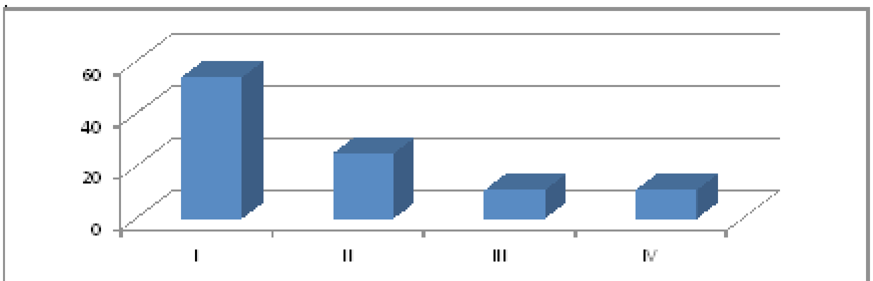


I	A vector because I have to represent intensity, verse and direction (TV 100%, MF 24%)
II	A vector because it result as the sum of the two magnetic field (TV 0%, MF 70%)
III	A vector because it has verse and direction (TV 0%, MF 6%)

Figure 2. Argumentation concerning the need of using a vector as a formal entity

All the TV students argue referring to the different properties that had to be represented, while the majority of the MF students goes beyond this first level of argumentation expressing it in terms of the principle of superposition.

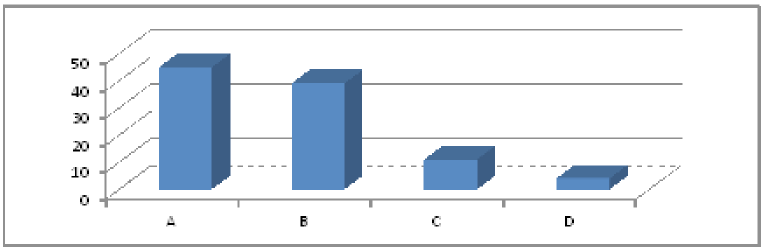
As concern instead the prevision of the way in which students proposed to extract the information from the draw of the field lines as concern the intensity of the magnetic field in each point of the paper, the distribution of the answers is almost the same in the all classes and could be summarized as in Figure 3.



I	The intensity of the magnetic field is proportional to the distance between the lines (54%)
II	The intensity of the magnetic field is proportional to the surface of the tubes constructed on the lines (25%)
III	The intensity of the magnetic field is proportional to the square of the distance between the lines (11%)
IV	NR (11%)

Figure 3. Distribution of the intuitive students' proposals to extract from the field lines representation, information concerning the intensity of the magnetic

How could be seen from data, the idea to correlate the distance and/or the density of lines with the intensity of the magnetic field is spread among the students and, even if it is not the right interpretation, it the usual angle of attach propose by the students to solve this issue related to the introduction of a metric in the field lines representation. In fact, after the performing of the Activity 16, the 84% of the students (categories A and B reported in Figure 4) explicit a correct statement for the definition of a two-way relation between the lines distance and the intensity of the magnetic field in one point and then, during the big group discussion, the proposal of reshaping of the pattern of lines in a way that ensure all tubes have all the same value of the product between the intensity of the field in one point and the section of the tubes (or the square of the height of the stripes) emerges in all of the groups.



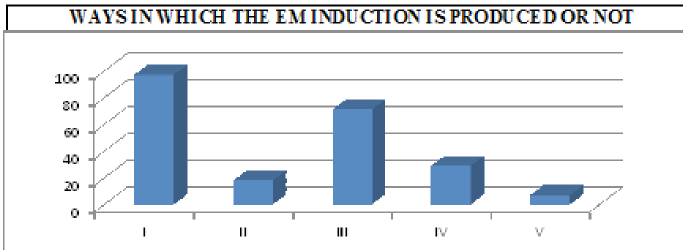
A	The intensity of the magnetic fields is equal to K/d^2 (45%)
B	The intensity of the magnetic fields varies inversely with the section of the tubes (39%)
C	Knowing the distance between the lines and from the pole can calculate it (11%)
D	NR (4%)

Figure 4. Students conclusions after the Activity 16 concerning the ways in which relate the intensity of the magnetic field and the property of the field lines representation.

To investigate when the magnetic field becomes a referent for the students, the analysis was focused on students' replies and argumentation to Activities 20 and 21.

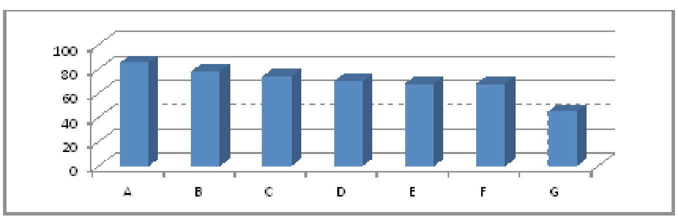
During the qualitative exploration of the electromagnetic induction, all the groups of students performed at least one way to produce the phenomena and explored the variables involved in the phenomena. Figure 5 gives an overlook of which were the observation done by the groups (in this case the category used in the reporting of the data are not mutually exclusive because each groups could provide more than one observation.

WAYS IN WHICH THE EM INDUCTION IS PRODUCED OR NOT



I	[GENERATE] Move the coils entering and exiting between the magnets (97%)
II	[GENERATE]Rotate the coils between the magnets (18%)
III	[NOT GENERATE] Move the coils between the magnet, when it is oriente perprendicular to the face of the magnets (71%)
IV	[NOT GENERATE] Coil at rest (8%)
V	[NOT GENERATE] Move the coil between the magnet - remaining between the magnet - (7%)

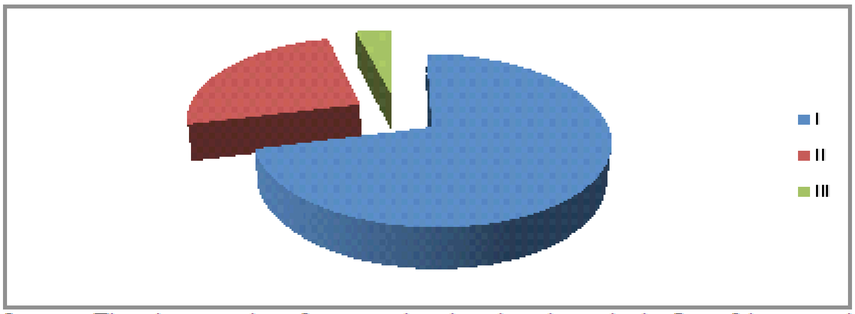
VARIABLES AND PARAMETER IDENTIFIED



A	The sign of the current change entering or exiting between the magnet (85%)
B	Speed of the movement (78%)
C	Transient nature (74%)
D	Inclination of the coils (70%)
E	Number of the windings of the coils (68%)
F	Radius of the coils (68%)
G	Distance between the magnets (45%)

Figure 5. Observation done by the students during Activity 20 as concern the ways in which generate (or not) electromagnetic induction and the individuation of the variables involved.

In addition, as concern the methodological aspect adopted by the students during the experimental exploration proposed, several groups perform a double check (they lowered and then raised the value of a parameters) denoting so a need of rigor and formality and highlighting also the need to construct, even in the qualitative case, a formalization of the correlation between the factors and the variables involved and several of them 71% use the flux of the magnetic field as a conceptual referents which its rate of variation among time produced the induced current. Looking at Figure 6, where are reported the replies to questions 20.3, there is also a 25% who refer to the lines without do manifestly references to the concept of flux.



I	There is generation of current when there is a change in the flux of the magnetic field going through the circuit (71%)
II	The current produced is proportional to the speed of the field lines variation through the coils, the number of windings and the radius of the coils (25%)
III	NR (4%)

Figure 6. General interpretation provided by students at the end of the qualitative exploration of the electromagnetic induction.

During the quantitative exploration, a minority of the students speaks in terms of field line and flux (36%), while the main part (63%) spontaneously correlate the physical situation with the phase of the graph in relation with the position and the movement of the magnet. As emerged in the class discussion, this trend were due to the difficult that the students has to see the movement of the field lines representation with the magnet.

Discussion and conclusions

By means of this experimentation is shown how an experimental exploration of the properties of a physical entity done in a prospective of gradual construction of the formal properties and allow student to construct the meaning of abstract entities giving physical meaning of their representation. In this way, the formal entity becomes a conceptual referent having a meaningful graphical representation that allow students to do prevision and provide interpretation of the explored phenomena. In particular the magnetic field became the main conceptual referent in situations in which the source of the magnetic properties is at rest, while some difficult persist when the sources are in motion. The role of the experimental exploration for the investigation of the induction phenomena as they were proposed have a double value: in the qualitative exploration students found and construct an explanatory model based on the abstract entity that they had characterized earlier; in the quantitative one, students overcome the limits in which the formal entity were experimentally formalized to provide a new parameters in the description of the field relating the movement of the lines with the source of the magnetic properties. So there is a double value of the experiment: validation and extension of the model.

Appendix A

Summary of the learning path and the inquired based learning path proposed.

1) I have got a box with several different objects in it. How could I recognize the magnets between the other objects?

2) hanging a magnet in one hands, approaching it to different materials: how many and which are the interactions do you foresight to experiment?

3) Design a procedure of exploration of the several interactions.

4) Let's do the experiment together. A) write the important elements that emerges from the explorations; b) on the base of the results obtained, summarize (categorizing) the observed interactions

5) A bar magnets lies on the table, approaching to it another magnet holding the second magnet in one hand. How do the two magnets interact?
Do a foresight, explain your foresight, represent graphically the process providing explicative comment of you representation.

6) Hang a magnet with a wire to a 'L' shaped bar.
a) Rotate the bar. Does the direction of the hanged magnet change?
b) approaching the hanged magnet with another magnet. Represents and justify the phenomenon
c) The interaction occurs even without a contact. How do you interpret this observation?
d) How do you represent it graphically?

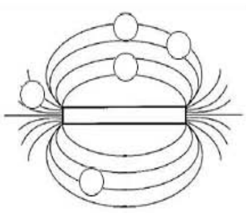
7) The compass.
a) How do you categorize the compass, as concern the way in which it interact with a magnet? Justify your answer.
b) Design an exploration that allows understanding the nature of the compass as concern the previous classification of object that we did. Describe it and explain your proposal.

8) Discuss with your group and report the group's decision

9) Do the exploration that you design in group providing your personal critical comments as concern the way in which the exploration was held and the results obtained.

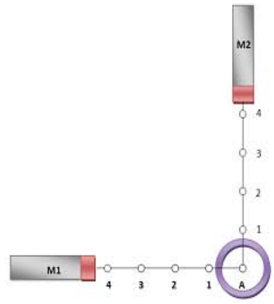
10) Every group presents its results to the class with the aim to reach a common conclusion: which is the category in which the compass had to be placed?

11) Fix a sheet of paper on the table and place a compass on it. Represent the shape of the compass and the direction of the needle.
a) rotate the compass leaving the compass on the same point. Does the direction of the needle change?
b) approaching a magnets to the compass while you are observing the needle of the compass. Describe how the needle of the compass moves and provide an explanation of it (eventually do several different experiment of approaching)
c) Paste a sheet of paper on a carton box and paste a magnet on the sheet. Using the compass as an explorer of the magnetic properties of the space, place it in several positions around the magnet. For each positions represent the direction of the needle: the choice of the position and the number of position needed to describe the distribution of the needles around the magnet is up to you.
d) Compare our drawing with the one did by the researcher and draw the lines of orientation as envelop of the direction took by the needle of the compass.
e) Foresight the direction of the needles of the compasses placed on the different lines represented in the next figure. Justify your answer.

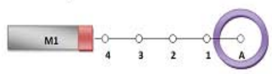


12) The lines of orientation in the surrounding of a cylindrical magnet. Describe the main characteristics of the pattern of lines of orientation.
a) are they symmetric?
b) does them intersect one each other? What does it means from a formal point of view? (in particular as concern the uniqueness of direction at each point)
c) How does the distance between lines change? Describe, qualitatively, the trend of the distance between the lines in the points around the magnet.
d) Foresight the direction of a ferromagnetic needle placed in the same point in which the compasses were placed in the figure of the question 11.e.
e) Observe a table of compass and a table of ferromagnetic needles. Describe similarities and differences between the two cases.

13) In the figure below, are represented 2 identic magnets M1 and M2 placed orthogonally one to the other with the same pole at the same distance to the point A.
a) represent the direction assumed by the needle of the compass in the point A.
b) explain the reasoning that you did to foresight the direction of the needle in the point A
Let's do some experimentations with the table of compasses to study the orientation of the needle changing the distance of one of the two magnet from the point A
c) Use a different color to represent in the previous figure the direction of the needle of the compass plased in the point A when the magnet M1 is placed in position 4,3,2 and 1.
d) How do you explain the changes in the needle direction at the approaching of the magnet M1 to the point A?

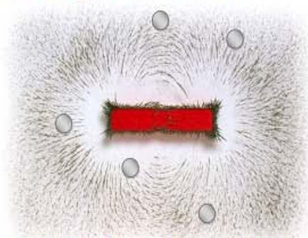


e) looking at the results obtained, which are the characteristic of the property (the physic quantity) that we explored in the space around the magnet in terms of orientation of the needle of the compass?
f) which formal (mathematical) entity you will use to represent this property of the space? Justify your answer.
g) Represent whit the formal entity that you choose the magnetic property of the space / the physical quantity that we had explored in terms of orientation of the needle of the compass.



h) describe your representation, justifying it
i) the points 1,2,3 and 4 lies on a line of orientation coincident with the axes of the magnet. Do you think that the physical quantity that represents the magnetic property of the space is constant along the lines of orientation of the needles? Justify your answer.
j) Is it a force?

14) A magnet is placed on a table with around itself 5 iron balls held in the positions shown in the figure. For each of the balls draw the magnetic field vector present at the point where the ball is located and what you think is the direction in which the ball will begin to move if it is will left to move.



14.1) Is the starting direction of the ball coincident with that one of the field line? ________ Explain your forecast explaining your reasoning
14.2) Do the experiment. Is it in agreement with your forecast? ________ Describe the motion of the balls as if you had to describe it to a your classmate.
14.3) The starting direction of the ball represents the direction of the resultant of the forces acting on the ball. In the previous situation (shown schematically below) represents the magnetic field vector and the forces acting on each ball.

15.1) Which is the mathematical entity that could we use to represent the magnetic properties in one point? Justify it.
On the base of these observation we can labeled it "magnetic field".
Using a magnetic field sensor, we will explore the intensity of the magnetic field along a line.
15.2) Do you expect that the intensity of the magnetic field along a line changes or remains constant? Justify your answer, on the base of the experimental observation did until now.
Misure it using a field line sensor.
15.3) Is it in agreement with your forecast? If no, reinterpret what you observed on the light of this observation.
Let's now look for a procedure that allows indicating the intensity of the magnetic field with the field lines representation.

Consider all the patterns you drew until now.
16.1) Does the lines intersect?
16.2) What types of surfaces are enclosed by the lines?
16.3) Thinking about the three-dimensional picture of the pattern of lines, what is the corresponding figure in three dimensions?
16.4) In analogy to what you did for the electric field, get one of these tubes and I calculate the magnetic flux within it.
16.5) What I have to do to calculate the magnetic flux through a pipe
16.6) Record the data in the following table where with "h" is labeled the height of the strip at the point where the measurement is carried out:

B	h	$\Phi(B)$

16.7) What could be argue looking at the data of the previous table?
16.8) Repeat the same measure considering other pipes recording the data in the following table:

	Tube 2			Tube 3			Tube 4	
B	h	$\Phi(B)$	B	h	$\Phi(B)$	B	h	$\Phi(B)$

16.9) Observe the collected data. What do you noticed?
16.10) Observed the constancy of Φ (B) in the various tubes, How this property could be used to ensure that the representation of the field lines will allow to obtain information about the intensity of the magnetic field vector for the points of the plane?

Sources of magnetic field

Remove all the objects from above and below the table.
17.1 Now we will try to discover if there are other sources of magnetic field. In your opinion, using a compass, how can you do to detect if an object has a magnetic field? Explain your answer
Compare your answer with the ones of the other groups.
17.2 Discuss and identify a common strategy. How will you do?
18.1 Take of copper. Has the copper a magnetic field? How do you plan to investigate it?
Connect the copper wire to a current generator (switched on).
18.2 Has the current-carrying copper wire its own magnetic field? Describe how to test this experimentally
Take a table of compasses and a copper wire carrying a current that goes through the table of compasses
18.3 How is the orientation of the compasses? Represent it
18.4 If instead of a single wire we had 2 copper wires carrying currents in opposite directions (see figure), are you able to represent the lines of orientation? Represent them below

O **X**

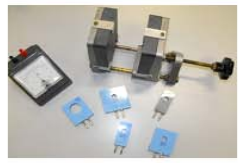
18.5 How did you construct the field lines in the figure above? Explain
18.6 Observe the simulation. Do you notice similarities and differences with the field lines of the magnet? Describe them

19.1 Consider a magnet and a wire carrying a current. Do you think there is an interaction between the two? Justify your answer
Do the experiment
19.2 Is the experiment in agreement with your forecast? Discuss it with your schoolmates to develop a shared explanation
19.3 Study qualitatively the phenomenon. From which parameter it depends? Test it

Parameters	Dependences?

19.4 Forecast the mathematical law which expresses the force: $\vec{F}$=....

Elettromagnetic Induction
20) [Qualitativelly]
We have seen that a circuit carrying a current is able to change the magnetic field in the space around it. We will investigate now if the reverse process is possible: starting from a magnetic field and a circuit can be generated a current? To reply to this question, an explorative activity will be proposed.
20.1 Use the available materials to perform the phenomena of the electromagnetic induction. Do several tests recording for each of them the observation done.
20.1 Which are the variables and/or the parameters involved? List them and explain (justifying) how these influenced the process. Remember to record also the tests that did NOT generate current.



1. Test done: ....
Explain end motivate why did you perform these test
....
Parameters and variables involved
....
Explain and justify the observation done:
....
2. Test done: ....
....
3. ..... 4. ..... 5. .....

20.1 Individuate a general rules that allows you to interpret all the observation you did.

21) [Quantitative exploration].
Place the cart on the guide and connect it to a magnet with an inextensible wire. Using a pulley hang the magnet out of the table and over a coils (as in figure). The coils is located at few centimeters from the ground and it is connected to a sensor of tension. Leaving the cart free to move, the magnet fall down through the coils and reach the ground.

BEFORE THE EXPERIMENT....
21.1) Which is the motion followed by the magnet?
21.2) Based on what you have observed in the previously qualitative exploration, forecast what will be the graph tension-time measured between the ends of the coils. Represent your prevision in a graph.

DO THE EXPERIMENT
22.1 Represent the graph obtained.
22.2 Compare the two graph highlighting analogies and commenting the differences.
22.3 Is the sign of the tension always the same? How do you explain it?
22.4 Which phases did you recognize into the graph?
22.5) Describe the graph associating to every phase the corresponding physical process related to this part of the graph.
22.6 Which is the part of the graph corresponding to the approaching of the magnet to the coil?
22.7 Which is the part of the graph in which the magnet goes through the coil?
22.8 Which is the part of the graph corresponding to the moving away of the magnet from the coil?
22.9 Report the maximum and the minimum value of the tension: V_{MAX} =______; V_{MIN} =______;
22.10 Are them equal? **V.11** How do you interpret it?
22.12 Measure from the graph the width at half height of the peak: $\Delta t_{V_{MAX}}$ =______ $\Delta t_{V_{MIN}}$ =______.
22.13 Are them equal? **V.14** How do you interpret it?
Measure the area of the tension-time graph
22.15 Areas of the first peak: ____ **V.16** Area of the second peak: ____ **V.17** Which is the value of the total area?________

References

Bagno, E., Eylon, B. S. (1997), From problem solving to a knowledge structure: An example from the domain of electromagnetism, *American Journal of Physics*, 65, 726–736.

Bradamante, F., Michelini, M., Stefanel, A. (2005). Learning problems related to the concept of field, *Frontiers of Fundamental Physics*

Guisasola J., Almudi J. M., and Ceberio M. (1999). Students ideas about source of magnetic field, II int. Esera Conf., 89-91

Maloney D. P., O'Kuma T. L., Hieggelke C.J. and Van Heuvelen A. (2001), *Physics Education Research, American Journal of Physics Supplement* 69 (7), S12-S23.

Thong, W.M., Gunstone, R.F., (2008). Some student conceptions of electromagnetic induction, *Research in Science Education*, Springer, London, 38 (1), 31-44.

Viennot L., Rainson S., (1992) Students' reasoning about the superposition of electric fields, *International Journal of Science Education*, 14 (4), 475-487.