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Design and evaluation of a research-based teaching sequence: the superposition of electric field

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This paper illustrates our approach to research-based teaching strategies, including their evaluation. It deals with a teaching sequence on the superposition of electric fields, implemented at college level in an institutional framework subject to severe constraints. The general approach to the teaching-learning processes is that of a motivated and guided construction. Consistently, this sequence was designed on the basis of two interrelated studies: a content analysis of the domain and an investigation of common ways of reasoning. Thus, the part played by multicausality in the superposition principle and the tendencies previously observed in common reasoning as regards the analysis of multivariable problems inspired the main choices made for this sequence. The evaluation method, using 'conceptual profiles', will be explained and illustrated with the main findings. A discussion of this approach ends the paper.

Introduction

After two decades of studies on ideas and ways of reasoning that are common among students, research in science education now concentrates more on investigating teaching-learning processes. A now widely shared view is that this cannot be done efficiently without a close reference to the particular content of what is taught.

The main reason for such a claim appears to be that learners' common ideas strongly depend on the content. In a constructivist approach (in a broad sense), it is essential to take such common ideas into account. We share this view. Whatever its implications for teaching, it means that what research can say about the teaching-learning process depends on the content.

But we find this argument alone too simplistic. The body of knowledge on which scholars agree at a given time could be regarded as a landscape which can be lit from different angles, observed from different perspectives and travelled by different paths. There is a wide choice, therefore a need for a decision, which will be by no means innocuous, in order to define the conceptual targets of a given teaching sequence. In other words, whereas a simplistic view would distinguish the 'what' of a teaching sequence from the 'how', we claim that both are inter-related and that the 'what' is to be specified in great detail after reasoned reflection, as Millar (1989) recommended. An analysis of the content is always necessary, even in the case of so-called 'elementary' topics. When this is carefully done, it becomes clearer how far some elements of the 'how' may react on the 'what' (see also Méheut 1997).

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Good examples of this way of designing a sequence are to be found in the teaching of electric circuits. Given the well known difficulties raised by electric circuits, especially sequential reasoning, several authors (Steinberg 1987, Licht 1991, Härtel 1993, White *et al.* 1993, Barbas and Psillos 1993, Sherwood and Chabay 1993, Psillos 1995, Chabay and Sherwood 1995) have chosen to emphasize the 'missing link between electrostatics and electrodynamics' to which Eylon and Ganiel also drew attention (1990), thus adopting a causal approach to the quasi-stationary state of a circuit. In particular, Sherwood and Chabay start with a battery with unconnected ends, then organize a step-by-step analysis of what happens when the circuit is closed until the quasi-stationary state is reached, i.e. until the current is the same in the whole circuit at any given time. Barbas and Psillos propose a similar approach to analyse what happens when one changes the conductivity of a part of a closed electric circuit. In these cases, it is clear that the 'hows' have been thought of in close connection with a 'what' that is itself far from neutral.

Our approach, like that adopted in the studies quoted above, is the direct converse of discovery learning. We think that the views of science need to be carefully introduced, in a top-down process among others, and that they cannot all just come out of debates between pupils presented with appropriate tasks. This last point was strongly emphasized by Johsua (1995) in his response to Lijnse's plea (1994) for teaching-learning scenarios which give the maximum weight to learners' freedom. In our sequence, conceptual evolution is accompanied on paths carefully designed as Millar (1989) recommended. Cognitive conflicts are organized, but they are not seen as panaceas, nor even as the necessary starting point for a conceptual progression. In this process, we see teachers as crucial protagonists.

We are not saying that knowledge should be transmitted, as opposed to personally constructed by students. As Ogborn *et al.* (1996) wrote, 'to teach is to act on other minds who act in response'. Needless to say, motivation is necessary to make a response. In our view, the teaching-learning process should therefore take place in a context of motivated and guided constructive effort.

In this paper, we describe a sequence aiming at such concept-building on the particular topic of superposition of electric fields. This topic is of special relevance because a comprehension of it is a prerequisite for a basic understanding of electrostatics and, a fortiori, for a unified view of electrostatics and electric circuits. A previous investigation of students' common ideas in this conceptual domain has been conducted in France, Sweden and Algeria (Viennot and Rainson, 1992). In this paper, the main results of this study are summarized and the basic principles, constraints and results of our teaching sequence are described.

If the target knowledge is held to result from the illumination of a given 'landscape', from diverse viewpoints and with various intensities, this consistently leads one to set up a multidimensional evaluation. We elaborate on this point when describing the 'conceptual profiles' that were used to evaluate our sequence.

Principle of superposition and causality

This principle can be stated as follows:

> Any point charge creates an electric field at any point in space according to Coulomb's law. This field is independent of the presence or absence of other charges, and of the nature of the environment. The electric field existing at a point is the vectorial sum of electric fields created at this point by all the existing charges.

We will only consider situations of electrostatics or a quasi-stationary analysis of electric circuits without inductive effects. With this hypothesis, the contribution of an electric charge situated at a given point to the field existing at a given point is independent of the previous states of the system.

This statement is commonly illustrated with a diagram (figure 1) which shows a point M, surrounded by 3 charges, q_1, q_2, q_3, and the electric field that exists at point M when the charges have the positions indicated on the diagram.

To be a little more explicit, we might illustrate the fact that each charge is associated with its field by a transparency showing this charge and its field in some points, which is inversely proportional to the square distance, as in figure 2.

The procedure used to find the field created by the three charges at a given point might then be illustrated by superimposing the three corresponding transparencies. In other words, this means that the interaction between two point charges in space is the same as if these charges were the only ones in space.

The principle of superposition holds for systems in which several factors evolve at the same time, in electrodynamic situations as well as in electrostatics. This is why the comprehension of this principle is an essential condition for reaching a unified view on these two domains.

Why should this seemingly obvious and easy principle be a subject of didactical research?

The superposition of electric fields concerns situations defined by several factors and it is now well known that problems with several variables raise considerable difficulties.

Previous investigations on this point (De Kleer and Brown 1981, Andersson 1986, Gutierrez and Ogborn 1992, Rozier and Viennot 1991, Viennot and Rozier 1994) show that these difficulties can be associated with the following tendencies:

- to ignore a cause if no effect is visible,
- to associate a cause with only one effect, forgetting the other effects,
- to consider only one cause for a given effect.

Causal reasoning, when reduced in this way, does not favour a systemic view and may in particular contribute to sequential reasoning in analysing electric circuits.

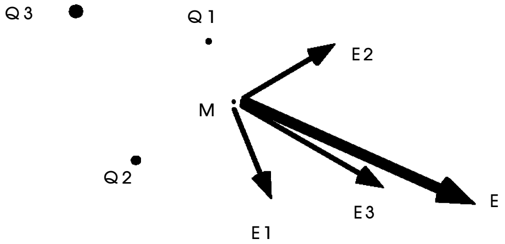


Figure 1. An illustration of the principle of superposition for three charges: the component of the field due to each charge is the same as if this charge was alone in space.

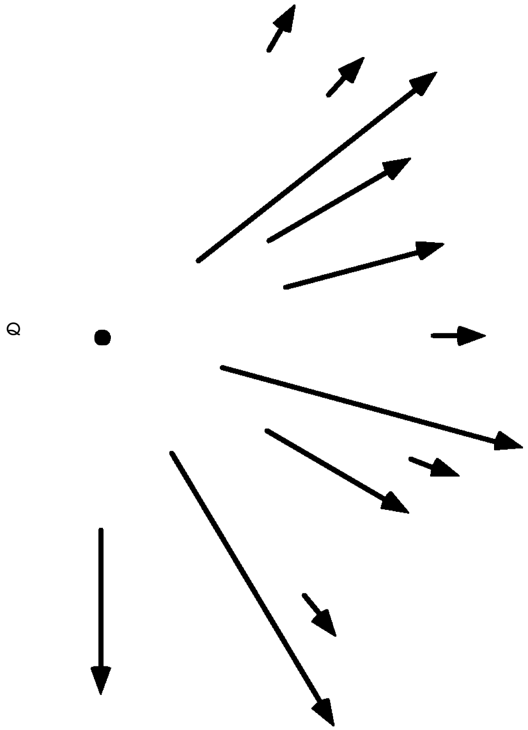


Figure 2. A diagram that, reproduced on a transparency, illustrates the indestructible (Coulomb) link between a charge and its field.

These previous results indicate that some difficulties in using the principle of superposition are to be expected. This is why an investigation of students' ideas in this specific domain has been carried out.

Investigation of students' reasoning in electrostatics

After ten preliminary interviews, an inquiry was conducted with seven questionnaires, put to 1,837 students in France, Sweden and Algeria (Viennot and Rainson 1992, Rainson *et al.* 1994)). The students comprised four samples of different academic levels, ranging from those in the 'Première scientifique' (grade 11) to those in their final year at university.

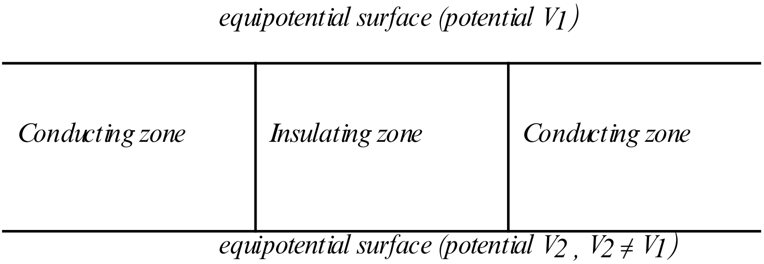
Two main problems were identified.

'Field only if mobility'

This label means that students have difficulty in accepting the existence of an electric field in a medium where charges are motionless.

Three paper-and-pencil questionnaires were used on this topic. In response to a questionnaire about insulators, many students gave an answer of the following type: 'charges cannot move in an insulator, therefore there is no electric field'. Another questionnaire presented conducting and isolating zones joining in parallel two conducting plates of different potential (figure 3). Students were asked to

In the situation represented in the drawing below, the two equipotential surfaces are infinite planes, perpendicular to the plane of the figure. Describe the electric field between the two surfaces.



In your opinion, are the electric fields in the conductor and in the insulator:

different ☐ *equal* ☐ *I don't know* ☐

Justify your answer.

Figure 3. The Neapolitan Ice Cream questionnaire.

compare the values of the field in these different zones. The difficulty expected was that of considering the existence and value of the electric field irrespective of the effect of this field and therefore admitting that the field was the same in the different zones (edge effects being neglected).

We put this questionnaire (Rainson *et al.* 1994) to different populations from grade eleven to second year at university ($N = 420$). Although it increased with the academic level, the rate of correct answers was less than 50% in each sample.

Many incorrect answers (about 40% in each sample) were accompanied by comments such as:

> The electric field is only present in the conducting zones. The role of an insulator is to isolate as suggested by its name, and then it would dampen or suppress the electric field.
>
> As the electric field is responsible for the electric current and as the currents are different in the conductor and in the insulator, then the fields are different.
>
> The permittivities are different.

So, the obstacle linked with the greater or lesser mobility of charges seems very important.

Cause in the formula

The second main obstacle shown by this investigation might be labelled 'cause in the formula'.

Already suspected because of the results of a questionnaire on Gauss's theorem (Viennot and Rainson, 1992), this obstacle consists of ignoring the sources of the field that are not represented by their symbol in the formula which gives the field. In the case of Gauss's theorem, for instance, this leads to denying the influence on the existence and value of the field of any charged object situated outside the surface considered .

This restriction is therefore of the 'one cause is enough' type , with the additional feature that the cause identified is implicit 'in the formula'. This obstacle is the focus of a teaching sequence that we implemented and evaluated during four successive years. For this reason, it will be described below in greater detail than the first.

This obstacle has been demonstrated principally with a questionnaire concerning a point charge near a conducting body: 'Near a Conductor' (NC, figure 4).

An expected difficulty is the following. Even if one knows the formula $\mathbf{E} = \sigma/\varepsilon_0\mathbf{n}$, and even if one is able to demonstrate it with Gauss's theorem, it is not obvious to keep in mind the meaning and domain of validity of this relationship. As for Gauss's theorem, the possible presence of external charges is not acknowledged by any symbol in the formula, hence the risk of forgetting that the existence of external charges does not invalidate this relationship. A delicate point is that an external charge contributes to the field in two ways: via a direct contribution (Coulomb force) and via a change in the surface charge density σ (influence), whereas the latter (adaptive) quantity is sufficient to calculate the field.

A complete set of correct answers (figure 4) is observed in only 8% of answers (N = 252), for students in a class of 'Mathématiques Spéciales' or in second year at university in France (or equivalent level in Sweden).

Among incorrect answers, the most frequent arguments are of the 'cause in the formula′ type:

> As the value of the field is $\sigma/\varepsilon_0\mathbf{n}$, the origin of the field is the conductor because the charge density is on the conductor and nowhere else.

In such comments, the students improperly ascribe a causal status to the expression $\mathbf{E} = \sigma/\varepsilon_0\mathbf{n}$. Given this formula, '$\sigma$' is considered as the only source of the field.

In many answers (one third), it is difficult to see whether the student is aware of both the direct and indirect effects (the created field and the change in the surface charge density respectively) of the external charge. Among the students (18%) who mention both influence and superposition in their comments, some clearly show a lack of comprehension of the situation:

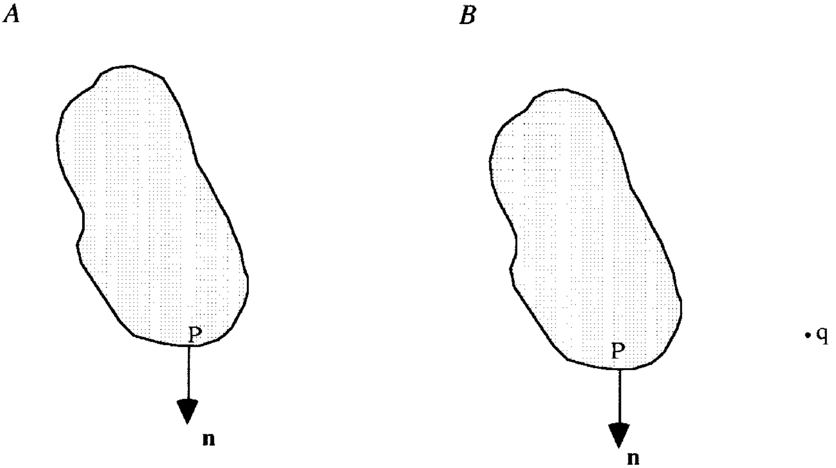
> $\sigma' \neq \sigma$ because of influence and $\mathbf{E} = \sigma'/\varepsilon_0\mathbf{n} + q\mathbf{u}/4\pi\varepsilon_0 r^2$.

In such cases, the students seem to grasp the superposition, but they fail to understand that the result of this superposition is included in the expression $\sigma/\varepsilon_0\mathbf{n}$, where the value of the surface charge density σ results from all the charges in the Universe.

At a point P on the surface of a conducting material, charge carriers being static, the surface charge density is σ. $\boldsymbol{n}$ *is defined as the normal unit vector to the surface at P, pointing outwards. Outside the conductor, at a point very near P, the electric field is* $\sigma/\varepsilon_0\boldsymbol{n}$.

1—Is this field due to the charges in the vicinity of P, all the charges of the conductor, or all the charges of the universe (choose the right answer and justify)?

2-–Given the two situations below (A: conducting body alone in space, B: same body with an external charge nearby), answer the following questions:



a) In situation B, will the electric field $\boldsymbol{E}$ *at a point very near P be given by the formula* $\boldsymbol{E}= \sigma/\varepsilon_0\boldsymbol{n}$?

b) Is the electric field outside the conductor, at a point very near P, the same in situation A and B?

c) Is the surface charge density σ *the same in situation A and B?*

Correct answers:

—The sources of the field near a conducting body, $\sigma/\varepsilon_0\mathbf{n}$, are all the charges in the universe" (and not only charges situated on this body);

—if an external charge is situated in the vicinity of the conducting body, the electric field very near this body, at M, is different from the field that exists in the absence of an external charge, the value of σ changes because of influence, but the formula $\mathbf{E}(M) = \sigma/\varepsilon_0\mathbf{n}$ still holds. In particular, $\mathbf{E}$ is still orthogonal to the surface considered (see also figure 5a).

Figure 4. The "NC" questionnaire, on the field near a conductor, and correct answers.

In order to validate this hypothesis, we set up a second version of this questionnaire. Situation B of the previous test is presented, as well as the definitions of the implied quantities. Then the following questions are put:

> A student suggests the expression $\mathbf{E}(M) = \sigma/\varepsilon_0\mathbf{n} + \mathbf{E}_q$, where $\mathbf{E}_q$ is the field due to q at M. What do you think? Is the expression right ?(explain why), wrong ?(explain why and give the correct expression), ambiguous ? (explain why and give an unambiguous expression).

A large proportion of the students (a third, N = 141) think that the formula is right, thereby confirming the hypothesis produced to interpret some answers to the preceding version of the test. Moreover, numerous incorrect arguments can be found, such as:

Since σ changes, the formula ought to have been written $\sigma'/\varepsilon_0\mathbf{n} + \mathbf{E}_q$.

Finally, 75% of the students clearly show that they do not understand the situation.

Thus, in this complex case which involves multiple field sources, students have difficulty in envisaging all the effects of a given cause (the direct effect, a field is created; the indirect effect, influence), and in envisaging all the causes for a given effect: i.e. in taking into account all the sources of a given field near a conducting body.

The fact that these difficulties seemed resistant to normal teaching, as well as a textbook analysis (Rainson 1995), induced us to design a teaching sequence. It was decided to try first to overcome the obstacle 'cause in the formula' in order to lead students to a good mastery of the superposition principle in a static situation, leaving aside for the time being the second obstacle: 'field only if mobility'.

The teaching sequence(s): main features

This pedagogical intervention was designed within the very rigid boundary conditions of a class of 'Mathématiques Spéciales Technologiques', with a set syllabus, not much teaching time and the additional factor of strong competition at the end of the year . The sequence concerned mainly conductors in equilibrium. The syllabus and the global teaching time was the same as for a normal class, which we consider important for evaluation purposes as well as for the 'usability' of our sequence.

This means that the sequence is not characterized by spectacular changes in contents or 'teaching methods', but only by qualitative changes that might a priori be considered as 'small'.

Three versions of the sequence were successively designed and implemented between 1991 and 1995. (The teacher was S. Rainson.) The first sequence S_0 (1991–92) was almost indistinguishable from a very traditional one, the only difference being that the teacher was aware of the difficulties and insisted carefully on the critical points. The second version of the sequence, S_i, was implemented in 1992–93. Only the final version S_f (implemented in 1993–94 and 1994–95) was fully informed by our investigation concerning students' difficulties. We describe this final sequence, and indicate for each element the versions in which it was introduced. A more detailed description of the three versions of the sequences can be found in Rainson (1995).

Given the results of our investigation on students' ideas, aspects related to causality were increasingly stressed throughout our successive attempts. Consequently, our final sequence emphasized the following aspects:

Multiplicity of causes

This first aspect was especially underlined by two elements of our strategy:

1. Use of transparencies (S_i, S_f), each attaching a given field to a given charge (both being represented in the same colour), whatever the rest of the situation. This permitted a visual illustration of the solidarity between charge and field which is implied in the superposition principle (see above). In this symbolisation, the presence of several charges in the situation corresponds to several superposed transparencies. This strategy prevents a charge in a

given place from being considered without its field being considered at the same time.

2. Systematic presence of external charges when illustrating theorems (S_f): In addition to the "strategy of transparencies", we decided to show explicitly the great power of basic theorems concerning electrostatics. This power resides in their great generality. Thus, a very basic theorem such as "$\mathbf{E} = \mathbf{0}$ inside a conductor at equilibrium" holds, whatever the external charges. In the same way, the boundary conditions concerning, for instance, the components of an electric field near a surface are the same, whatever the rest of the world. In all these cases, a very simple formula sums up the effects of a multiplicity of causes, including charge carriers that have moved in an adaptative process until equilibrium is reached. Our previous investigation prompted us to highlight the presence of external charges systematically when dealing with such theorems.

These strategies concern mainly the teacher's explanations. The next points appeal to more active participation of students.

Multiplicity of effects

The situation described in the NC test, i.e. a conducting body with a point charge nearby, has been extensively analysed (S_i, S_f). The sources of the fields inside the conducting body and near the conductor (of respective values zero and $\sigma/\varepsilon_0\mathbf{n}$) were raised and discussed in class, in order to illustrate the direct and indirect effects of the external charge. For this analysis of superposition and influence phenomena, a transparency similar to those described above (say, green) was used to represent the external charge and its field, while another transparency (say, red) illustrated the charges on the conductor in the presence of an external charge, as well as the field created by this charge. It was intended, in particular, that the students would be struck and motivated by the fact that the field created by the charges on the conductor ('red') was not perpendicular to the surface of the conducting body (figure 5a). It was expected that students' motivation would be increased by this kind of surprise.

Studying static situations as the result of a transformation

The preceding strategy was adopted during the first versions of the sequence, and turned out to be of very limited efficiency. A destabilization occurred without subsequent restabilization, i.e. the field's sources were often correctly taken into account with the outcome that the direction of the field was incorrectly constructed (figure 5b).

Considering the importance of causality in students' difficulties, we tried to place even greater emphasis on causal analysis (S_f). With this purpose in mind, we decided to emphasize *changes* in the physical situation under scrutiny, at the expense of purely static analyses.

The situation of a conducting body with a point charge in the vicinity was therefore raised again with the following question: 'What changes if the point charge is displaced: the field created by this charge, the field created by the conducting body, the total field, the value of σ?' A short debate in class followed. In

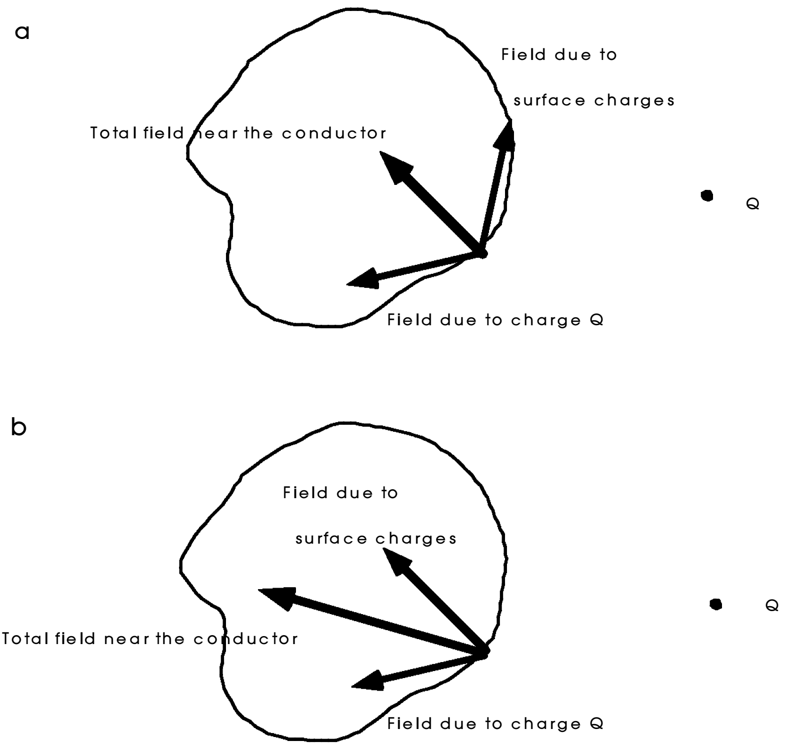


Figure 5. Correct construction (a) and frequent mistake (b) concerning the field near a conductor in the presence of an external charge.

the same way, this situation was discussed, with the charge staying at the same place but having a different value. Thus, we expected that the link between the external charge and its field would not only be seen as a simultaneous occurrence, but also as a causal link, on the same footing as the influence effect.

This procedure did not increase the total class time devoted to the topic.

Evaluation of the sequence

Method and samples

In order to evaluate this teaching sequence, we used a paper and pencil questionnaire, after teaching electrostatics, with different control and test groups. All the groups had had the same syllabus and had devoted very similar amounts of time to the topic of electrostatics, i.e about fifteen hours.

This evaluation was conducted in four successive years (see Rainson 1995), but we used the same test only in the last three years. For this reason, only the results corresponding to these three years will be given. The test and control groups that were involved in this evaluation are described in table 1. As regards the control groups, the 'C_1' students were at approximately same level of academic competence as the test students. The 'C_2' students had followed the same syllabus, but they were, from an academic point of view, much brighter.

Table 1. Test and control groups for the first (S_i) and final (S_f) versions of the sequence.

	Groups	*Year*	*Sequence*	*N*
Test groups	$\varnothing$	1992–1993	S_i	38
	T_2	1993–1994	S_f	39
	T_3	1994–1995	S_f	34
	$T_f = T_2 + T_3$		S_f	73
Control groups	C_1	1992–1993		107
	C_2 (higher ability)	1993–1994		39

The questionnaire, labelled 'Conductor in capacitor' ('C in C'), is given in figure 6.

This test was devised to investigate different aspects of students' knowledge. The overall teaching time on electrostatics being the same for all the groups, we thought it important to assess how far the expected improvement in students' understanding in line with our teaching goal – to increase the use of causal reasoning in the analysis of electrostatic phenomena – was obtained at the expense of more traditional knowledge, direction and value of electric fields in such and such situation. The four first items bear on values of fields and are therefore of the latter type, whereas the four items at the end of the test bear on sources, i.e. explore how students reconcile a causal interpretation of the fields with their properties.

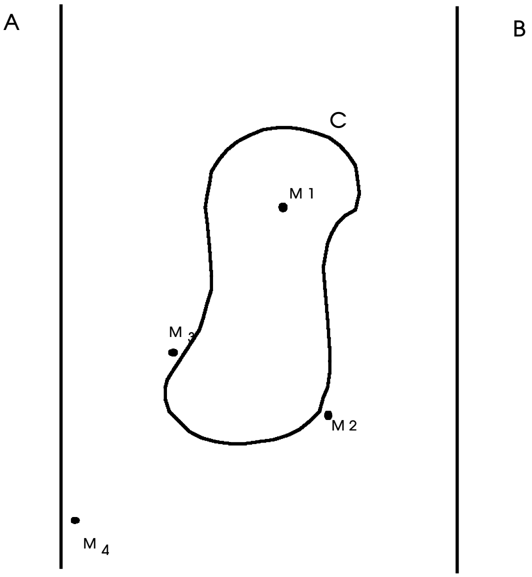
The achievement of each group is shown in a 'conceptual profile' in each case (Mortimer 1993, Viennot 1994, Chauvet 1994, 1996 a, b). Each point of such a profile is the rate of occurrence of a given element in the answer for a given item in the question ('couple'). In order to interpret these data, we group together the couples 'element(s) in answer/item in question' that we assume to be in principle similar. Such an assumption may be based on very different grounds. In Mortimer's case, concerning the physical state of matter, the different zones of the conceptual profile were determined on the basis of epistemological and ontological aspects of successive theories (with less explicit attention to the influence of the question). In Chauvet's case, concerning the topic of colour, the grouping was intended to mirror a type of competency: physics, techniques of arts, psychology of perception. In our case, we organize our grouping along two lines: 'traditional knowledge' (value and direction of fields), 'causal analysis' (sources of the fields). The 'families' of couples are defined in table 2.

Results

Figure 7 shows the profiles obtained in this way, for each of the three test groups T_1, T_2 and T_3. Given their similarities, we grouped T_2 and T_3 into a single one, T_f (the suffix f holds for 'final sequence'). The results of the control groups are given in figure 8 as well as those of test group T_f.

Let a conducting body C , initially neutral and isolated.

Let a plane capacitor, with empty space between plates (A, B), charged and isolated ($Q_A > 0$). C is placed between A and B (see schema). This setting is at electrostatic equilibrium.



The following positions are considered:
M1, inside C,
M2, M3, outside C, near its surface,
M4, between the plates of the capacitor, near plate A.

Represent the electric fields $\mathbf{E}_1$, $\mathbf{E}_2$, $\mathbf{E}_3$, $\mathbf{E}_4$, existing respectively at points M_1, M_2, M_3 and M_4. Justify your schema.

What are the sources of $\mathbf{E}_1$?
What are the sources of $\mathbf{E}_2$?
What are the sources of $\mathbf{E}_3$?
What are the sources of $\mathbf{E}_4$?

Figure 6. The "C in C" questionnaire, about a conductor in a capacitor.

Several aspects emerge from the shape of the profiles. A first comment can be made concerning the preliminary grouping of couples in families. This grouping was assumed to mirror similarities between questions, similarities supposedly witnessed by a relationship between corresponding rates of answers.

In fact, we observe some discrepancies between rates inside a given family. In family 1 for instance, couple n°2, which concerns M2 and M3, is clearly less frequent than the others. By contrast, couple n°5 in family 2, which concerns the same points, is more frequent than the other couples of this family. In terms that would be more familiar in an ordinary teaching context, M2 and M3 are the points for which it is at the same time the most difficult to give the right direction of the field and the easiest to correctly enumerate the sources of this field. A remarkable feature of our results is that this relative 'difficulty' is observed in all the test and control groups, i.e. to return to our terminology, the 'shape' of a piece of profile limited to a given family is stable over all the groups. We consider this stability as an a posteriori validation of our tentative grouping in families.

Table 2. Couples 'elements of answers/item of question' used in the evaluation of the sequence.

	Couple	*Element(s) of answer*	*Item of question*
Family 1	1	correct (zero) value of the field...	... at M_1
Traditional knowledge	2	correct direction (perpendicular to the surface) of the field...	... at M_2 and M_3
	3	correct direction (perpendicular to the surface) of the field...	... at M_4
Family 2	4	correct identification of the field sources...	... at M_1
Causal analysis	5	correct identification of the field sources...	... at M_2 and M_3
	6	correct identification of the field sources...	... at M_4
Family 3	7	Correct value and sources...	... concerning M_1
Synthesis	8	Correct direction and sources...	... concerning M_2 and M_3
	9	Correct direction and sources...	... concerning M_4

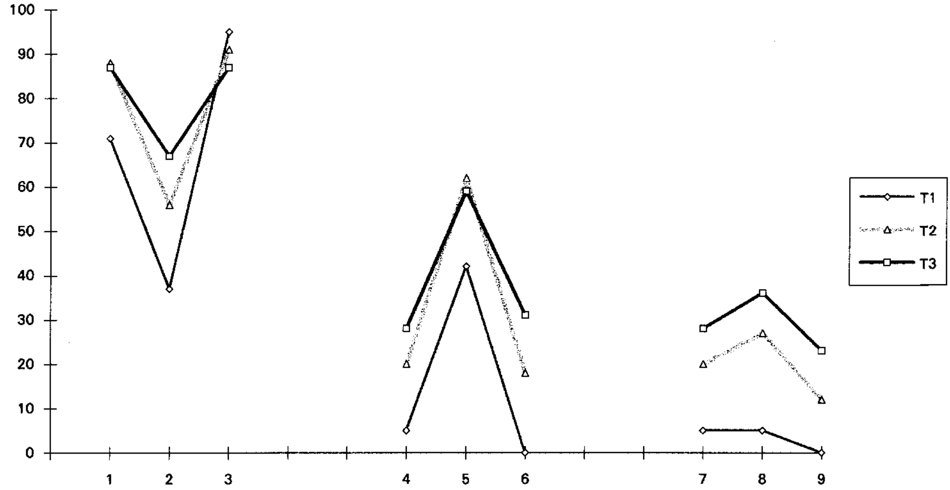


Figure 7. Profiles of the three test groups, T_1, T_2 and T_3 (table 1): per- Figure centages of occurrences of "couples" n° 1 to 9 (table 2).

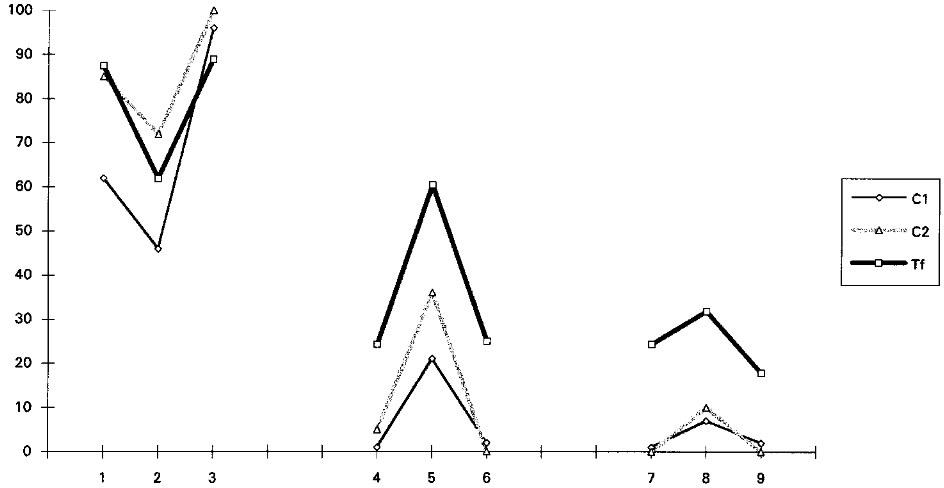


Figure 8. Profiles of test group T_f, and of control groups C_1 and C_2 (table 1): percentages of occurrences of "couples" n° 1 to 9 (table 2) .

Conversely, the different groups may show very different overall levels of occurrence for each family (for $\chi 2$ tests, see Rainson 1995).

First, the control groups are very different as regards traditional knowledge (family 1), a result that was expected given the high ability level of group C_2 as compared to the normal group C_1. A somewhat unexpected finding was the similarity in their very poor causal analysis, as observed through the very low occurrence of couples of families 2 and 3 in both groups.

Concerning family 2, in other words a correct causal analysis, an improvement occurred between sequence S_i (test group T_1) and the final sequence, S_f (test groups T_2 and T_3). Moreover, the already higher level of causal analysis observed in test group T_1 as compared to both control groups is accompanied by a low occurrence of couples of family 3. In other words, the understanding of sources and values of the field has not yet been reconciled after sequence S_i. As already mentioned (see also fig 2b), the total field is often represented as the vectorial sum of a component normal to the conducting body and of a component normal to the plate of the capacitor, an error not commonly observed in control groups. It looks as though the improvement in causal analysis was obtained at the expense of traditional knowledge, or else as though a destabilisation occurred without subsequent restabilization.

A comparison between test group T_f (final sequence) and the control group of highest ability level, C_2, indicates that these groups are analogous if seen through the filter of 'family 1', with C_2 having a slight edge, whereas the test group clearly shows a better comprehension of the causal aspects involved in families 2 and 3.

This positive result should not be overestimated: not more than about a third of the test students can be considered as having reached the target level of understanding (against 10% for the control group of higher ability, and 7% for the control group of the same ability as the test group).

Concluding remarks

Two conclusions can be drawn from this investigation. First, the part played by causality in students' reasoning seems not to be solely a source of difficulties. It can also be instrumental in facilitating students' understanding of content in which causal aspects seems to be obscured by a very synthetic formalism. Only when causal aspects have been strongly emphasized in teaching did a noticeable, although modest, progress towards integrated understanding of superposition and influence phenomena occur. The important resistance of students' difficulties in this respect must also be considered. We agree with the above cited authors (see introduction), that a unified comprehension of electrostatics and electric circuits can be fostered by teaching strategies which emphasize causal aspects and transient phases. But such strategies rely on a mastery of the superposition principle. Our results suggest that this principle may be far from obvious to students, and that it is useful to work on it in static situations before analysing electric circuits.

Second, it is worth noting that this investigation was carried out in a context subject to severe constraints, not in principle very appropriate for didactic research. We were therefore obliged to act, as it were, at the margins, and the challenge was to show that so-called 'small' changes can do more than commonly expected. It was also necessary, in view of the above mentioned constraints, to show that there would be no loss in traditional knowledge to offset against the benefits of less standard teaching goals. This might be seen as a narrow-minded consideration. On the contrary, we suggest that the price to be paid for an assumed improvement is a matter that needs to be addressed when evaluating innovative sequences. It seems, in any case, to be very relevant to teachers in an ordinary context, and this at least deserves attention. We therefore suggest that techniques for multidimensional evaluation should be discussed, improved, and more commonly used.

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