INT. J. SCI. EDUC., 1992, VOL. 14, NO. 4, 475–487

# Students' reasoning about the superposition of electric fields

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This study concerns students' ideas about the superposition of electric fields. Two paper-and-pencil questionnaires were given to university students to investigate possible obstacles to a correct use of this principle.

The results confirm an expected difficulty about Gauss's theorem, i.e., the idea that only 'internal' charges create a field on a given closed surface. Another more surprising finding is that students are reluctant to admit that a field can penetrate into, or go out of, an insulator, particularly because 'charges cannot move'.

These first findings are discussed in connection with common features of students' reasoning about mechanics and about multivariable problems. Some directions of future research are proposed.

## Introduction

Reasoning about electric circuits has been extensively investigated in secondary schools as well as at university level (Hartel 1982, Closset 1983, Cohen *et al.* 1983, Riley 1985, Dupin and Johsua 1987, Shipstone 1984, 1985, Shipstone *et al.* 1988). Among the observed difficulties, one is especially resistant to teaching: students tend to adopt sequential reasoning in which an event occurring at a given point in a circuit only affects quantities further downstream (Closset 1983, Shipstone 1984, 1985). Instead, in the accepted 'quasistatic' analysis, the circuit should be seen as a system where several variables change simultaneously under the constraint of several relationships. In this accepted view, a local change in the circuit affects the whole circuit.

Some pedagogical suggestions to overcome this lack of a systemic view of circuits and this sequential approach have been made in recent years. In particular, special attention was given to analogies which emphasize the interactive aspects in the circuit (Hartel 1982, Closset 1983). A need to lead students towards 'voltage minded', rather than 'current minded', reasoning was stressed by Cohen *et al.* (1983). In order to give meaning to the notion of voltage, Psillos *et al.* (1988) suggest focusing on charge concentration at the ends of the battery. Licht (1987) places emphasis on the charge concentration at different points in the circuit. However, Benseghir and Closset (1991) underline the dangers of a careless identification between voltage and differences in charge concentration.

These recent studies and debates support Eylon and Ganiel's (1990) plea for the improvement of students' understanding of 'macro–micro' relationships. Their findings amply show students' difficulties in seeing the role of electric fields in the interplay of the different elements of a circuit. But the electric field itself, and more generally the notion of fields, has not been at the centre of any research on students' reasoning.

0950-0693/92 $3·00

## The study

After a preliminary phase of interviews and questionnaires, we chose to focus on the principle of the superposition of electric fields created by different systems of charges. This seems of interest for two reasons:

1. This principle is very basic in electrostatics and more generally in linear physics.
2. Teaching experience shows that practically all students accept and spontaneously use this principle – be it correctly or not – for calculating the field created by several charges of given positions in empty space. The point under study in this exploratory inquiry is to what extent this seemingly obvious idea of superposition is resisted when students are confronted with more complex situations.

A set of paper-and-pencil questionnaires was developed and given to different samples of university students in France and Algeria, before or after courses at different levels in electrostatics. The first questionnaire (Q1) deals with a topic where difficulties about the principle of superposition are *a priori* to be expected, namely in Gauss's theorem. The flux of a field created by charges that are external to a given 'Gauss's surface' is zero inside this surface. This is expected to induce the idea that the field created by such charges at a point inside the surface is also zero. The question that then arises is whether students will adopt this idea despite the fact that it contradicts the principle of superposition. The second questionnaire arose from answers to Q1 which showed that the notion of insulators may create obstacles to a correct addition of electric fields. We then decided to investigate this point in greater detail with a set of two questions, Q2 and Q3.

In this paper, questionnaires Q1 on the one hand, Q2 and Q3 on the other, are presented in two separate sections (A and B), each with the corresponding findings. The main reason for this unusual format is that the physical situations involved are rather different, and that neither the correct answers nor the students' comments are very easy to understand. It therefore seems more appropriate to concentrate successively on each type of problem. The three questions bring together pieces of information about the same points: is the principle of superposition a conceptual tool available to students? If not, can we characterize some common obstacles to an appropriate usage of this principle?

The three questions concern insulators, i.e., bodies in which, roughly speaking, charges cannot move. This choice was made to simplify, as far as possible, the questions and the interpretation of the answers. The phenomenon of polarization is not at the centre of this study, but will be taken into account in the interpretation of the answers, when necessary.

## The questionnaires

### A. Superposition of fields and Gauss's theorem

#### *1. Question and correct answer*

The first part of our investigation relies on a paper-and-pencil questionnaire, Q1, also referred to as the 'Gauss questionnaire' in this paper (see figure 1).

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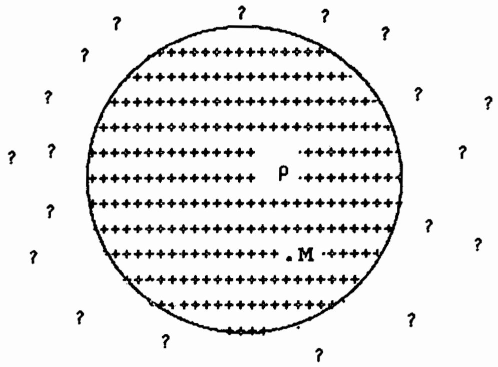
Q1



An insulating sphere of radius $R$ is charged with a *uniform* density of charge $\rho$. The distribution of charge outside the sphere is unknown. One would like to calculate the electrostatic field at a point $M$ located inside the sphere, that is to say at a distance $r$ from the centre such that $r < R$. Is it possible to make this calculation without knowing the distribution of charge outside the sphere?

If YES, WHY?, and HOW?
If NO, WHY?

EXPLAIN YOUR ANSWER IN DETAIL

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**Figure 1. The first questionnaire (Q1).**

The correct answer is NO. Indeed, whatever the conductivity of the sphere may be, the following expression of the theorem of superposition is valid:

> $\vec{E}_{\text{total}}$ (at point $M$) $= \vec{E}_{\text{int}}$ (at point $M$, due to charges in or on the sphere) $+ \vec{E}_{\text{out}}$ (at point $M$, due to charges outside the sphere)

Here, because the sphere is an insulator, the only displacement of charges that can occur in the influence of external charges is local and is due to polarization.

### 2. *Samples*

Two samples of university students were questioned:

G1 students in their second year at the University of Paris 7, in France ($N = 108$);
G2 students in their second year at the University of Setif, in Algeria ($N = 29$).

All these students had taken at least one course about electrostatics, which included Gauss's theorem and the equilibrium states of conducting bodies. The G2 group had also taken a course about dielectrics. We do not intend to present a formal comparative study of the students' knowledge in these two countries. At this exploratory stage, our goal is simply to see if the same difficulties are present in groups of rather different background.

The questionnaires were administered during a class period and students had 20 minutes to answer, which in fact means that they were not limited in time. They were invited to express themselves completely and in an anonymous way.

### 3. *Analysis of results*

(*a*) *The answers*
Table 1 shows the percentages of answers in terms of 'Yes', 'No', '?' (which means 'I don't know'), or 'no answer'.

(*b*) *Comments on the correct answer: 'No'*
The correct answer is sometimes accompanied by arguments mentioning the superposition of fields or the contribution of the external distribution of charges to the field at point *M*, for instance:

> One must take into account the external density of charges. But I don't know why it has always been neglected. *M* will be submitted to the field $\vec{E}_1$ due to $\rho_{\text{int}}+\vec{E}_2$ due to $\rho_{\text{ext}}$. $\vec{E}$ inside can be the algebraic sum of the two densities. (G2)

In other comments, it is not clear whether the external distribution of charges is still considered as acting directly on point *M* after other effects ('modified density of charges' in the insulator, 'polarization',...) have occurred:

> If there are other distributions of charges, the sphere will be polarized, its density of charge will be modified→the response No. (G2)

This question may even be asked for seemingly quite 'transparent' comments:

> The distribution of external charges can modify the field inside the conductor. (G2)

As the reasons given for this correct answer range widely, we cannot give any precise percentage for each type of the above comments, and we cannot warrant that *all* these 'correct answers' rely on a comprehension of the principle of superposition. This point will be discussed below.

(*c*) *Comments on the incorrect answer: 'Yes'*
The answer 'Yes', massively given in every sample, is justified with comments that can be classified under two main categories:

(*i*) *Misunderstood Gauss's theorem*: Many students in the two samples (see table 2) give arguments relying on the fact that, in Gauss's theorem, only the 'internal' charge would matter, for instance:

> Yes, [a calculation using Gauss's formula appears here] we only need the total internal charge. (G1)
> Yes, using Gauss's theorem only puts into play the internal distribution of charges. (G1)
> Yes,... [a calculation using Gauss's formula appears here] external charges do not influence the interior of the sphere. (G2)
> Yes, [a calculation using Gauss's formula appears here] it is precisely why the Gauss's theorem is so valuable! (G2)

**Table 1. Answers to the 'Gauss questionnaire' (Q1).**

| *Sample* | *N* | *Yes* (%) | *No* (%) | *?* (%) |
|---|---|---|---|---|
| G1 | 108 | 83 | 15 | 2 |
| G2 | 29 | 86 | 14 | 0 |

**Table 2. Comments for 'Yes' answers to the 'Gauss questionnaire' (Q1).**

| *Sample* | *Rate of 'Yes'* (%) | *Misunderstood Gauss's theorem* (%) | *Insulator* (%) |
|---|---|---|---|
| G1 | 83 | 49 | 15 |
| G2 | 86 | 72 | 10 |

(*ii*) *Insulators and electric field*: Some arguments rely on the fact that the sphere is an insulating body:

> Yes, because the sphere is an insulator, it has no connection with the exterior.... (G1)
> The sphere is an insulator, there is no interaction between internal and external charges. G1)

Sometimes another idea is added – charges cannot move:

> The sphere is insulating, therefore charges are 'frozen', therefore the external distribution of charges does not influence the field at $M$. (G1)
> The internal charges are motionless, therefore the internal field is constant whatever the external field produced by external charges may be. (G1)

In the text, the sphere is only said to be 'an insulating sphere' but the schema suggests that it is also isolated from the ground. In some comments, the two ideas of 'insulating' and 'isolated' body do not seem to be clearly discriminated:

> Yes, the sphere is insulated, it depends only on internal charges. (G1)
> One can calculate $E$ at point $M$ only knowing the distribution of charge inside the sphere because the sphere is insulated, therefore there is no influence of the external mediun on this sphere, → the sphere keeps its charge and $\vec{E}$ at $M$ keeps the same. (G2)
> As the sphere is an insulator, the internal charges are isolated from the external ones, which therefore have no effect on the field at a point inside the sphere. (G1)

We have regrouped all these 'Yes' answers linked with this idea of insulation, and have given their corresponding percentages in table 2. In some comments, the argument concerning the insulating property of the sphere is followed by a calculation of the electric field with Gauss's theorem. These comments have not been counted in the preceding section, because the misunderstanding of Gauss's theorem that they show is not the very basis of the argument.

### *Discussion*

There are few correct answers to this questionnaire in the two samples. Sometimes, the correct answers explicitly rely on the principle of superposition. Other arguments, however, recall a very common way of reasoning identified by Rozier and Viennot (1991): linear causal reasoning. In situations where the *simultaneous* influence of several factors should be taken into account, this way of reasoning gives rise to 'story-like' comments. Such arguments are based on a sequence of simple events that are considered as *successive*, each causing the following one. Here this would give: 'A charge is placed somewhere, then the insulator gets polarized, then there is a field created at point $M$', i.e., practically identical with one of the comments quoted above. The question then arises whether or not the students mentioning such an indirect effect consider that the direct effect of the charge is still present in the equilibrium state when finally reached. Our results leave this question unanswered.

The most serious finding of this questionnaire is a very high percentage, in all our three examples, of the expected error, which is to ascribe the field in the sphere uniquely to 'internal' charges. The total 'internal' charge '$Q_{\text{int}}$', in fact the total charge *inside the Gauss's surface*, is indeed mentioned in the formula giving the flux $\Phi$ of the field through this surface:

$$\Phi = \frac{Q_{\text{int}}}{\varepsilon_0}.$$

This fact seems to endow '$Q_{\text{int}}$' with a kind of causal exclusivity. One can also imagine that such a focus on the interior also works considering the symmetry of the problem: if the interior is symmetric, that is enough, in students' minds, to use the flux in a simple way to calculate the field. Whatever the precise mechanism of such reasoning, a very striking fact is that the principle of superposition is implicitly denied and does not help students in their answers.

Much less frequent arguments, relying on the idea of insulation, and sometimes of the mobility of charges, also deserve attention. The next section focuses on this point.

## B. Electric fields and insulators

### 1. *Questions and correct answers*

Two short questions about electric fields and insulators, Q2 and Q3, were asked in a single paper-and-pencil questionnaire (see figure 2). In both cases, the correct answer is that the considered charge creates an electric field at 'point $M$'. The theorem of superposition holds for all materials. According to the conductivity of these materials, displacements of charges may or may not occur. But, at any time, the

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Q2 A point charge is outside an insulating body. Does this charge create an electric field at a point $M$ inside this insulating body (see schema below)?

YES ☐ NO ☐

WHY?

Q3 A point charge is inside an insulating body. Does this charge create an electric field at a point $M$ outside this insulating body (see schema below)?

YES ☐ NO ☐

WHY?

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Figure 2. The second questionnaire (Q2 and Q3).

total field integrates the effect of every charge. Here, the bodies considered are insulators that get polarized when an additional charge is nearby (in, or out of, the body). The total field anywhere is then the sum of the field due to polarization and of the field created by this additional charge.

### 2. *Samples*

This questionnaire was presented to three types of students in scientific courses at university level in France:

G3 students in their first year after baccalauréat, having had no course in electrostatics at university, $N=64$;
G4 students in their second year at university, having had a course in electrostatics up to Gauss's theorem but without the chapter about dielectrics, $N=25$;
G5 students in their second year at university, having had a course in electrostatics, chapter about dielectrics included, $N=64$.

All these students had taken courses in secondary school about electric circuits, and had been taught some ideas about electric fields, e.g., the $\vec{F}=q\vec{E}$ relationship, used to calculate the motion of particles in the uniform field existing between the plates of a capacitor. In France, Coulomb's law is introduced after baccalauréat. As in the case of the Gauss's questionnaire, our study is only exploratory and we do not claim to make a formal assessment of students' ideas versus their academic level. Our results in this respect are only indicative.

The conditions under which the questionnaire was administered are similar to those described for Q1: 20 minutes during a class period, anonymous answers.

### 3. *Analysis of results*

#### (*a*) *The answers*

Table 3 shows the percentages of answers to each question, Q2 ($\vec{E}\rightarrow$into . . . ?) and Q3 ($\vec{E}\rightarrow$out . . . ?), in terms of 'Yes', 'No', or '?' (which means 'I don't know') or 'no answer'. An additional category has been used to classify the answers: '$E=0$' means that the students did not directly answer the question that was asked, 'does the charge create a field at $M$?', but used a periphrase: 'the field at $M$ is zero'. We have not considered this answer as equivalent to a 'No' because it might mean that the total field at $M$, due to 'charge $q$' plus other unspecified charges, is zero.

One can see from table 3 that the percentages of correct and incorrect answers, respectively, follow a rather predictable evolution between the samples G3 and G5, i.e., from the less to the most '*a priori* competent' group of students.

Table 4 gives the percentages of combined answers: identical answers to both questions, 'Yes–Yes', 'No–No' or others, for instance '?–?', on the one hand, and different answers to Q1 and Q2, 'Yes–No', 'No–Yes' and others on the other hand.

One can see from table 4 that taking into account pairs of answers smoothes out a lot of the differences observed between samples. As usual, students' comments are essential in order to interpret their answers. We used the following categories, which are not all necessarily linked with a definite answer (Yes, No, ?), as can be expected concerning a rather complex conceptual domain. These categories have been shown to permit the most significant groupings.

**Table 3. Answers to questionnaire about insulators (Q2 and Q3).**

| | | *Question 2 (%)* | | | | *Question 3 (%)* | | | |
|---|---|---|---|---|---|---|---|---|---|
| *Sample* | *N* | *Yes* | *No* | *E=0* | *?* | *Yes* | *No* | *E=0* | *?* |
| G3 | 64 | 42 | 42 | 2 | 14 | 27 | 64 | 0 | 9 |
| G4 | 25 | 36 | 48 | 0 | 16 | 60 | 20 | 4 | 16 |
| G5 | 64 | 64 | 23 | 8 | 5 | 67 | 25 | 0 | 8 |

**Table 4. Pairs of answers to both questions about insulators (Q2 and Q3).**

| | | *Similar response Q2–Q3 (%)* | | | | *Different response Q2–Q3 (%)* | | | |
|---|---|---|---|---|---|---|---|---|---|
| *Sample* | *N* | *Yes–Yes* | *No–No* | *Others* | *Total* | *Yes–No* | *No–Yes* | *Others* | *Total* |
| G3 | 64 | 14 | 30 | 6 | 50 | 28 | 15 | 11 | 54 |
| G4 | 25 | 28 | 16 | 16 | 60 | 4 | 32 | 4 | 40 |
| G5 | 64 | 48 | 8 | 3 | 59 | 16 | 16 | 8 | 40 |

(*b*) *Comments justifying a positive answer* (*q creates a field*...)

The most clearly correct comments observed with positive answers (in 'Yes–Yes', 'Yes–No' or 'No–Yes' combined answers) are similar to one of these instances:

> Charge $q$ creates a field in the whole space, therefore also at point $M$. (Q2, G3)
> Yes, because an insulator does not influence a field but it is not conductor for the currents. (Q2, G3)
> An insulating body does not stop an electric field. (Q3, G3)
> Charge $q$ creates a field in the whole space. (Q3, G4)
> Charge $q$ creates a field at a point $M$ equal to
>
> $$\vec{E}=\frac{q}{4\pi\varepsilon_0}\frac{\vec{r}}{r_3}$$
>
> Because it creates a field in the whole space. (Q2, G5)
> Because $q$ creates a potential around the insulator. (Q3, G5)

Sometimes the arguments are quite questionable:

> The surface is around the charge, one may use Gauss's theorem. (Q3, G5)

or

> Yes, charge $q$ will produce a field at point $M$ inside the insulating body. As the charge at point $M$ is zero, there will be a potential difference between the two considered points. (Q2, G3)

Finally, some comments mention the existence of polarization in the insulator (see table 5):

> Yes, charge $q$ polarizes the insulator. (Q2, G4)
> Yes, because a field is created by polarization. (Q5, G4)

Again it is not always clear whether, after having caused the polarization, charge $q$ is still considered to contribute directly to the final field: we find here the same

**Table 5. 'Yes' answers to questions about insulators in which polarization is mentioned.**

| *Sample* | *N* | *Question 2* (%) | *Question 3* (%) | *Students* (%) |
|---|---|---|---|---|
| G3 | 64 | 0 | 0 | 0 |
| G4 | 25 | 0 | 0 | 0 |
| G5 | 64 | 8 | 12 | 16 |

**Table 6. Types of comments to questionnaire about insulators (Q2 and Q3).**

| | | *'Blocking role of insulators'* (%) | | | *'Field if mobility'* (%) | | |
|---|---|---|---|---|---|---|---|
| *Sample* | *N* | *Q2* | *Q3* | *Students* | *Q2* | *Q3* | *Students* |
| G3 | 64 | 34 | 37 | 44 | 16 | 14 | 25 |
| G4 | 25 | 8 | 20 | 28 | 16 | 4 | 20 |
| G5 | 64 | 9 | 9 | 19 | 8 | 5 | 14 |

ambiguity already pointed out and discussed in section A. In fact the last of these quotations strongly suggests that only the indirect effect of charge $q$, i.e., the one through polarization, is considered.

A precise sorting out of these comments given with a 'Yes' answer is difficult and we will not attempt to draw a line between correct arguments and those that are less clearly correct. Broadly speaking, for each question and in every sample, the percentage of unambiguous and correct explanations is less than a third of the percentage of correct answers.

### (*c*) *The blocking role of an insulator*

This idea can be very straightforwardly expressed: 'No, because $q$ (or $M$, according to the question) is in an insulator'. More often, the idea is more developed, for instance:

> The insulating property of the body prevents the field from penetrating it. (Q2, G3)
> The insulating body is globally submitted to the electric field created by $q$. But point $M$ is not submitted to this field because it is protected by the insulator. (Q2, G3)
> The insulator prevents any type of ray getting in. At the surface, the ray is not reflected, but it cannot go through. (Q2, G3)
> The insulator blocks the field inside the body: this field cannot be created again after the insulator. (Q3, G3)
> Because it is an insulator: it does not exert any force on the outside. (Q3, G5)

All these arguments are given with the answer 'No' to Q2 or Q3. We have put in this category every comment mentioning this single idea of 'insulation' (see table 6). The corresponding percentage of answers decreases rather drastically (44%→19%) with the academic level of our samples.

### (*d*) *Charges cannot move, therefore there is no electric field or, more briefly, 'field if mobility'*

We have put under this heading every comment where a link was made between the non-existence of an electric field and the impossibility of charges moving in the insulator. Such comments have not been included in the preceding category even if they mention the word 'insulator', because they are more specific.

Sometimes, this link between field and mobility seems to be made for the 'point *M*' located in the insulator, in response to Q2 ($\vec{E}\rightarrow$into . . . ?), for instance:

> As this body is an insulator, the charges inside are motionless. If *q* created a field, the charges in the body would then be submitted to an electric field. (Q2, G4)
> As no charge is free around *M*, there cannot be any electric field at point *M*. (Q2, G5)
> The charge does not create any field. Otherwise, there would be a potential, and a potential difference: one would have a current passing through this body, which is impossible because of the insulator. (Q2, G5)

In other comments, observed in both questions, it seems as if, to create a field at point *M*, a charge would need to send 'electrons' or 'protons' up to this point:

> The protons or the electrons sent by *q* cannot reach *M* inside the insulator because this body insulates. (Q2, G3)
> The insulator is an obstacle to the motion of electrons between *q* and *M* (Q2, G3)
> No, because electrons and protons will not be able to escape out of, or to propagate in, the insulator, therefore they will not go out of this body to reach point *M*. (Q3, G3)
> No, . . . the charge stays inside the insulator and cannot be captured. (Q3, G4)

Finally, on Q3 ($\vec{E}\rightarrow$out . . . ?), some students say that some charges must move around or away from (?) 'charge *q*', for this charge to be able to create a field:

> Charge *q* does not create an electric field at point *M* because the insulator blocks every motion of electrons. (Q3, G3)
> As there is no possible motion of charges in the insulator, there cannot be any field created at point *M*. (Q3, G5)

It is not always possible to discriminate between these different meanings of comments linking the mobility of charges and the existence of a field, in a comment such as this for instance:

> Because there cannot be any motion of electrons. (Q2, G3)

This is why we have kept this single broad category: 'field if mobility'. Comments classified in this category are nearly all found with a response 'No', '?' or '$E=0$' to either question. Only three comments of this type have been found with a positive response:

> Internal charges cannot escape out of the insulator, but external charges can penetrate into it. (Q2, G3)
> Charge *q* creates an electric field at a point *M* inside the body because this body is made of mobile particles. (Q2, G3)
> Outside the body, the medium is conductor, charges are free to move, therefore *q* will be able to create a field at *M*. (Q2, G4)

The percentages of answers corresponding to this 'field if mobility' type, are also shown in table 4. They decrease slowly with the level of competency of our samples (25%→14%)

### (*e*) *Charges at point M?*

Some rare comments link the existence of a field at point *M* with the presence of charges at this point, without any allusion to mobility at all:

> ?, it all depends on the charge at point *M*. (Q3, G3)
> No, because the point is neutral from an electric point of view. (Q3, G3)

As rare as they may be, they deserve attention. They might be very close to some of those classified in the 'field if mobility' type, specifying that 'protons' or 'electrons' would have to reach point $M$ for a field to exist there. They throw some doubt on the meaning ascribed by students to the $\vec{F}=q\vec{E}$ relationship: would this formula suggest that no field can exist at a given point if there is no charge placed at this point? Such comments also introduce a doubt about the actual meaning of arguments (quoted in section B3b) which, in Question 2, mention 'polarization', i.e., the existence of charges near point $M$.

### 4. *Discussion*

These results present some striking features. The first is the low percentage of correct answers (Yes–Yes) even after a complete course in electrostatics in second year at university. Correlatively, there is a high percentage (40% or more) of answers which are different for the two questions. Some comments show a deliberate discrimination between the two situations, but they are relatively rare, and more probably the predominant phenomenon is an instability in students' reasoning.

The main ideas that seem to influence students' reasonings are the following:

- If a body is an *insulator*, the field is blocked either in (for an 'outgoing' field, Q3), or at the boundary of (for an 'incoming' field, Q2), the body. This idea, already observed in the 'Gauss questionnaire', is probably linked with the word 'insulator' itself. The fact that the words 'insulated' and 'isolated' are sometimes not clearly discriminated in students' comments probably goes with the same type of verbal obstacle. The importance of this obstacle seems to decrease rapidly with the level of students' academic competence, although it is still non-negligible after a complete course on electrostatics (G5, 19%).
- There cannot be any electric field at a point where *charges* cannot *move*. This may be an electric version of the well-known link established by students between force and motion (Viennot 1979), and/or a distorted interpretation of the $\vec{j}=\sigma\vec{E}$ relationship, linking the ideas of field and current. More deeply, students might need to imagine an effect to accept a virtual cause. This type of answer is less frequently observed than the preceding one for students starting their higher education (25% versus 44%), but it is nearly as frequent (14% versus 19%) for students having had a complete course of electrostatics (G5).

More rarely, other ideas are expressed:

- There cannot be any electric field at a given point if there is no force acting on a charge placed there, so there cannot be a field if there is no charge at this point. This might come from a distorted interpretation of the $\vec{F}=q\vec{E}$ relationship, and/or, again, from a need to have an effect to accept the existence of a virtual cause.
- Some 'electrons' or 'protons' must be travelling from the active charge to a given point for an electric field to exist at this point.
- Charges need to move to be able to create a field. This might be an outcome of the 'field if mobility' idea combined with a confusion between active and passive agents in the electric interaction. This last feature of reasoning has been observed for other kinds of interactions (Viennot 1985).

Adding up the percentages of answers corresponding to these ideas, one finds that, after a complete course in electrostatics in second year at university, a third of the students think that insulators block the electric field.

There are relatively few comments mentioning an *indirect effect* of the 'active' charge at point $M$ (in Q2 or in Q3) through polarization of the insulator. This was partly predictable because the only students who had taken a course on dielectrics were those from the G5 sample and some from G4 who took the course for the second time. But even in G5, such comments are not very frequent. Anyway, we observed in these comments traces of a way of reasoning, linear causal reasoning, that does not envisage all the charges present in the final state of equilibrium as *simultaneously* contributing to the field.

## Concluding remarks

Although exploratory, this study clearly shows some students' difficulties in the understanding of electric fields.

The significance of our findings using the 'Gauss questionnaire' (Q1) is not that it shows that 'Gauss's theorem' is poorly understood by students. This is a well established fact. It is to pinpoint one of the components of this incomprehension, i.e., that students do not spontaneously use the principle of the superposition of fields created by all the charges of the universe to determine their answers.

Another difficulty, shown by the results of the two questionnaires, is a link between the existence of a field and the mobility of charges. Again a striking fact is the ineffectiveness of the idea of superposition in students' reasoning. This principle does not help students form their answers, and it is apparently swept aside by more important considerations which focus on the effects of electric fields.

It is worth noting that certain aspects of electric fields are successively introduced in different contexts: motion of particles between the plates of a capacitor ($\vec{F}=q\vec{E}$), microscopic Ohm's law in electric circuits ($\vec{j}=\sigma\vec{E}$), electrostatics ('the field is zero inside a conductor'), Maxwell's equations.... If the effects of the electric field are so important in the way students grasp this concept, it is important to analyse the impact of these different contexts, and to look for ways of unifying the patchwork of ideas that may result from their successive introduction. We therefore suggest that we should not only follow Eylon and Ganiel's (1990) proposal concerning an early semi-qualitative teaching of macro–micro relationships *in electric circuits*, but also more explicitly to link, at least at college level, the electrostatic view of the electric field *in the whole space* with the electrodynamic aspect of this concept.

## References

BENSEGHIR, A. and CLOSSET, J. L. (1991). Transition between electrostatics and electrodynamics: historical difficulties and students' reasoning. Internal report, on request from the authors.

CLOSSET, J. L. (1983). Sequential reasoning in electricity. In *Research on Physics Education: Proceedings of the First International Workshop* (pp. 313–319). Paris, Edition du CNRS.

COHEN, R., EYLON, B. and GANIEL, U. (1983). Potential difference and current in simple electric circuits: a study of students' concepts. *American Journal of Physics*, *51*, 407–412.

DUPIN, J. J. and JOHSUA, S. (1987). Conceptions of French pupils concerning electric circuits: structure and evolution. *Journal of Research in Science Teaching*, *6*, 791–806.

EYLON, B. S. and GANIEL, U. (1990). Macro–micro relationships: the missing link between electrostatics and electrodynamics. *International Journal of Science Education, 12* (1), 79–94.

HARTEL, H. (1982). The electric circuit as a system: a new approach. *European Journal of Science Education, 4* (1), 45–55.

LICHT, P. (1987). A strategy to deal with conceptual and reasoning problems in introductory electricity education. In J. Novak (Ed.), *Misconceptions and Educational Strategies in Science and Mathematics: Proceedings of the Second International Seminar* (pp. 275–297). Ithaca, NY, Cornell University.

PSILLOS, D., KOUMARAS, P. and TIBERGHIEN, A. (1988). Voltage presented as a primary concept in an introductory teaching sequence on d.c. circuits. *International Journal of Science Education, 10* (1), 29–43.

RILEY, M. S. (1985). Structural understanding and problem solving skill. In R. Duit, W. Jung and C. V. Rhoneck (Eds.), *Aspects of Understanding Electricity: Proceedings of an International Workshop, Ludwigsburg, 1984* (pp. 165–195). Kiel, IPN.

ROZIER, S. and VIENNOT, L. (1991). Students' reasoning in thermodynamics. *International Journal of Science Education, 13* (2), 159–170.

SHIPSTONE, D. M. (1984). A study of children's understanding of electricity in simple d.c. circuits. *European Journal of Science Education, 6*, 185–198.

SHIPSTONE, D. M. (1985). On children's use of conceptual models in reasoning about current electricity. In R. Duit, W. Jung and C. V. Rhoneck (Eds.), *Aspects of Understanding Electricity: Proceedings of an International Workshop, Ludwigsburg, 1984* (pp. 73–93). Kiel, IPN.

SHIPSTONE, D. M., RHONECK, C. VON, JUNG, W., KARRQUIST, C., DUPIN, J. J., JOHSUA, S. and LICHT, P. (1988). A study of students' understanding of electricity in five European countries. *International Journal of Science Education, 10* (3), 303–316.

VIENNOT, L. (1979). Spontaneous reasoning in elementary dynamics. *European Journal of Science Education, 1* (2), 205–221.

VIENNOT, L. (1985). Analysing students' reasoning: tendencies in interpretation. *American Journal of Physics, 53* (5), 432–436.