Chapter 6

STUDENTS' UNDERSTANDINGS OF PHENOMENA RELATED TO FIELDS

The previous chapter was concerned with students' representations of fields, and did so by means of finding groupings in students' answers and describing them with the SOLO Taxonomy. This chapter uses the same format as the preceding chapter for analysis and presentation, but differs in that it is concerned with students' use of their representations of fields to explain electrical phenomena. As such, this offers a further development of the research into these representations in the previous chapter. The use of field concepts to explain circuit electrical phenomena is of considerable interest, as it forms a part of many teaching sequences. The current chapter investigates what students made of the link between fields and circuits.

As it did in the previous chapter, the research question for this chapter arises from a combination of the topic-based research questions set out in chapter 3, combined with the nature of the theoretical framework used: How can students' understandings of these topics be described in terms of the SOLO Taxonomy? This involves attention to elements of students' thought, the relationship between them, and the difference between concrete and abstract responses. Following this procedure focusses and facilitates the primary objective, which is to describe students' understandings of the topic.

The first section is concerned with students' understandings of potential and voltage as they relate to fields. The concept of potential can be used to form a bridge between electrostatics and electrodynamics in teaching, so it is of interest to see whether students are capable of forming this link. Investigations of students' link between electrostatics and electrodynamics is the purpose of the second section, which is concerned with understandings of currents as they relate to field phenomena. The third and final section of this chapter deals with students' ability to use a particle model in their reasoning about these topics. These sections are outlined in table 6.1, which lists these three sections, with the headings dealt with in each section, and the questions from the test/interviews which are dealt with under each heading. This table corresponds to table 5.1 which served the same function for the preceding chapter. As in that table, questions from the test/interviews are identified by the use of a roman numeral for the number of the test/interview, followed by a digit showing the number of the question within that test/interview. For example, "III5" would indicate the fifth question of the third interview. Questions described in detail within this chapter are in bold face, while those in the appendix are in plain type.

TABLE 6.1

Aspects of students' understanding of phenomena related to fields

Potential and voltage:

Finding potential in a given field **I3**

Potential in fields, potential difference and circuit phenomena **I4**

Potential, potential energy and kinetic energy **I6**

Current:

Effects of ideas about circuits on ideas about fields I9, I10

Induced current and its relationship to understandings of fields **III1**

Particles and macroscopic phenomena:

Relation of moving particles to currents in magnetic fields **III5**

UNDERSTANDINGS OF POTENTIAL AND VOLTAGE

Potential is a key concept which links electric fields and electric circuits. It is a more abstract concept than field strength, and involves consideration of energy and work. A full understanding of the concept of potential requires an appreciation of the relationship between field strength and the energy required to move a particle through a field. The relationship between these involves integration of force along a path, quite a complicated procedure. This section examines responses to questions which required students to apply their understandings of electric fields to the idea of potential in circuits.

Three questions were developed to address these issues. The first question asked students to identify minima and maxima of field strength in a given electric field, and to compare this with the minima and maxima of potential in the field. This question shows the relationship between potential and field strength in students' minds.

The next question dealt with potential difference in the same electric field, asking the students what would happen if a wire were placed in that field. This question studied students' ideas of current and voltage in relation to electric fields. The question started with students' ideas about the field, and asked them to apply these to predict the behaviour of a conducting wire placed in this field. The intention was to have students make a link between the classical electrostatic situation and an electrodynamic situation involving the conducting wire. The final question was aimed at clarifying the relationship seen by the students between force, energy and voltage. This question involves movement of a particle between the plates of a capacitor, giving students the opportunity to use either potential energy considerations or else a misconception identifying force with voltage.

This range of questions covered the students' understandings of potential in field situations, as it relates to field strength, voltage, electric current and energy.

Finding potential in a given field

In this question (question 3 of test/interview 1), students were asked to proceed as follows:

(i) Can you represent the electric field of these two point charges? Draw field lines. [see figure 6.1]
(ii) On the above diagram, indicate clearly any points where the field strength will be: (a) a maximum - explain why; (b) a minimum - explain why.
(iii) On the above diagram, indicate clearly any points where the potential will be: (a) a maximum - explain why; (b) a minimum - explain why.

Figure 6.1 Two positive charges

This test question was intended to probe students' ideas about the relationship between field strength and potential. The field given in the question is a simple one, intended to give students a chance to answer without too many complications. However, there is the interesting feature that the minimum in field strength does not in fact correspond to the minimum in potential for this field. This is because field strength adds as a vector, and can therefore cancel, while potential adds as a scalar and cannot cancel in this case.

Parts (i) and (ii) of this question were dealt with at length in the section of the previous chapter relating to the field vector. The overall result from parts (i) and (ii) was that students did not, in general, use the idea of vector field in their thinking. Instead, they reasoned in terms of fields and field lines "squashing together", a much more concrete idea. This inability to use the field vector had implications for the students' view of potential in part (iii).

Electric potential appears to be a concept which cannot be expressed usefully in concrete symbolic terms. Most of the students, working from non-abstract ideas about fields, were unable to come to any coherent explanation of electric potential other than identifying it with field strength. The majority of their answers to part (iii) were, therefore, concrete symbolic.

Concrete symbolic responses

Responses in this mode either did not have a consistent picture of electric potential, or else identified potential with field strength. The seven students responding at the unistructural concrete symbolic level focussed on the single idea that potential was the same thing as field strength, for example, one student (s. 49) stated:

> (a) [a minimum] there is a min potential when field strength is min because there are no field lines
> (b) [a maximum] there is a max potential when field strength is max because there are field lines
> *Interviewer: O.K., when you talked about potential, what exactly is potential?*
> *Student: [long pause] Where the - the way I looked at it is where the magnetic field would be at its minimum [ie, this is where potential is minimum]. So it wouldn't be as strong, basically.*
> *Interviewer: O.K., is that the same thing as field strength?*
> *Student: [pause] Yeah, well, it probably would be.*

In the above unistructural response, one sees a simple identification of potential with field strength. The thirteen students responding at a multistructural concrete symbolic level also displayed the conceptual unit seen in the unistructural responses, that is, that potential is the same thing as field strength. At the same time, they also mentioned a number of other issues in their understanding of potential. These included energy, work, movement and voltage. While these issues have an inherent abstract character, the students used the words without being able to explain their meaning, as in one student's (s. 26) somewhat disjointed response,

> *Student: Potential is voltage. [pause] Yeah, it's just the same as saying voltage, isn't it?*
> ...
> *Interviewer: Well, what does the potential actually mean?*
> *Student: I reckon the potential means that the voltage drop from one point to another if you were - respect to there. Oh, potential would be the force needed to bring that - no that's potential energy, I'm getting really stuffed up here, yeah, I'm just having really trouble with potential, with two point charges I'm not sure at all what you mean. But I do think that the voltage - I remember talking about it in lectures, they say that with respect to infinity is counted as zero, but apart from that, I'm not sure what it means.*

In the above, the student has brought in the ideas of voltage, force, "one point to another", voltage at infinity. However, there was no integration in his picture, and these units remained separate. By contrast, the five students producing relational concrete symbolic responses were able to integrate their ideas around the concept of field strength. In the response below, the student (s. 54) talks about the field strength "doing work", and the field strength doing this work "to move it",

Interviewer: ... what is potential?
Student: ... at a certain distance from the charge itself there's going to be a certain [pause] potential which means um, if you go out that certain distance, [pause] the field strength created would do work on a test charge at that distance, to move it, I dunno, in, or repel it, depending upon the sign of the test charge and the sign of the charge itself.

In the above, the student used field strength to relate the ideas of work and movement when describing potential. However, he was not able to use the idea of work as an integrating factor, as seen below. The abstraction of the work/energy concept appears to be beyond him, and he avoids using the concept of work to describe potential, preferring to talk about the more tangible "strength of that force":

Interviewer: O.K., so potential has something to do with work, but what exactly?
Student: Well, potential is um, I dunno, it's a difference in I suppose you could say concentration, [pause] of a um, [pause] force, acting upon something.
Interviewer: Concentration of force?
Student: Yeah, like, well, probably in better words you could say the strength of that force. So at this point if it's stronger and at this point it's less, there's going to be like a drop, as you go between the two points.

The above inability to use the work concept as an integrating factor was characteristic of the concrete symbolic responses to this question Although these responses could mention the idea of work, and relate it to field strength, there was no ability to reason with the work concept as such. This only appeared in the formal mode.

<u>Formal responses</u>

The three students, whose responses were coded in this mode, were able to introduce the idea of work and energy into their understandings of potential.

Two of these students' responses were at the unistructural level, as they had the single idea that electric potential was the work involved when moving a charge between points. They could use this idea of work consistently. At the same time, their understanding of potential was incomplete, in that they still saw potential as having minima and maxima at the same points as the electric field strength. This was also the reasoning used by students responding in the concrete-symbolic mode. An example of one student's (s.21) response at the unistructural formal level is given below:

> *Interviewer: O.K., now what does potential actually mean?*
> *Student: Potential [pause] is [pause] potential energy really, in moving a positive point charge from one point to another, the loss in potential energy, which is obviously the gain in kinetic energy as you move that charge from one point to another.*

In the above, there is a clear use of the energy concept of potential, and its use in terms of particle movement in a field. But, as can be seen in the excerpt below, the student (s. 21) had not developed ideas about the meaning of potential at a point, or the idea of conservation that makes it possible to define potential at a point:

> *Interviewer: O.K., from one point to another? Now if you only have one point then how can you talk about a minimum or a maximum?*
> *Student: Yeah, what I did there was I just assumed you would be moving a charge placed at b in that field.*
> *Interviewer: To where?*
> *Student: Hmm, yeah, true. Just within that field, yeah, just depends how much you'd move it and all that sort of thing too.*

There is still an inability to describe potential as an independent entity which draws its meaning from the idea of energy conservation. This same inability was seen in the multistructural formal response discussed below.

The sole multistructural formal response focussed on more than one aspect of the formal definition of electric potential. There was mention of both the idea of mathematical integration of force to find the work done, and the idea of measurement relative to infinity. At the same time, this student (s. 32) still did not fully appreciate the abstract relationship between electric potential and field strength, predicting that the two would be proportional:

> Potential is proportional to the electric field strength at any point.
> *Interviewer: What does it mean to say the potential is a minimum?*

Student: It means that if you were to place a point charge ... the potential is the energy which that charge could pick up as it moved in whatever direction it's going to move, as you release it. Uh, well, as it moved to wherever it's going to, and if it's going to go to infinity, then you have to wait 'til it gets to infinity before you can measure the amount of energy that it's picked up. But of course you can integrate it a lot more easily than that.

The above excerpt is indicative of quite a complicated understanding of potential, involving energy considerations and the idea of measurement relative to infinity. However, the student still has difficulty fitting this in with the relationship between potential and field strength, and cannot come to a consistent final response:

Interviewer: O.K., you say that potential is proportional to the electric field strength at any point.
Student: It is, yes ... Well, as I was saying before about your point charge, which is going to accelerate off into the distance, it might find a point to stop at, but that's not really very likely. Its initial motion is always - no, its initial acceleration - is always going to be directly proportional to the electric field because F is equal to [pause] E q. So it's going to accelerate initially in that direction, assuming that you don't have any complicating factors, which can't really help, I don't think, I haven't thought about that before I started explaining. As it accelerates off into the distance, it's still going to have um, the same... You know, this has just made me question my entire explanation of what potential was. Yeah, initially, it's definitely proportional, the acceleration is definitely proportional to the electric field, but I'm not so sure now about what is going to happen to it afterwards.

In the above quote, there is a statement that the initial acceleration is proportional to the field strength. This statement is true. However, the student was unable to come to the concept that potential is dependent on the integral of field strength across distance to infinity, rather than the field strength at that point. This leaves him at a multistructural level in the formal mode. One hypothesises that the relational level in this mode would correspond to an understanding of the relationship between potential and field strength in energy terms, with students being able to distinguish between maxima of field strength and maxima of potential.

Conclusion about finding potential in a given field

All students believed that field strength and potential were either proportional or identical. The idea of field strength is far less abstract than the idea of potential, which makes field strength easier for students to grasp. Even the students who were beginning to appreciate potential in relation to work and energy still viewed it as proportional to field strength. A full understanding of the relationship between potential and field strength would appear to be the next step in building a relational formal understanding of potential. Operating at a significantly lower level, the students who were thinking more concretely had only a collection of phrases about potential. The concept of potential would seem to be abstract, and inherently in the formal mode. This finding comes from a study of students' understandings of potential in fields. The following question examines students' ability to relate this idea of potential in fields to their ideas about potential difference and current in circuits.

Potential in fields, potential difference and circuit phenomena

The question just discussed explored students' ideas about potential as it relates to field strength. The present question was intended to connect these ideas about potential in fields to potential difference in circuits. This connection, between electrostatics and electrodynamics, was of particular interest in light of previous suggestions in the literature that this was a missing link in students' minds (Eylon & Ganiel, 1990). This question followed directly after the question just discussed, and was question 4 of test/interview 1.

(i) In the diagram [figure 6.2], the two circles with "+" signs are positive point charges. Rank the potential energy of small charges placed at A, B and C. Explain the reasons for your answer.
(ii) (a) Is there a potential difference between points A and B in the diagram above? (yes/no). Explain.
(b) Will a current flow if a wire is placed between A and B? (yes/no). Explain.
(c) If there is a current, would it ever stop? (yes/no). Explain - if "yes", when would it stop?

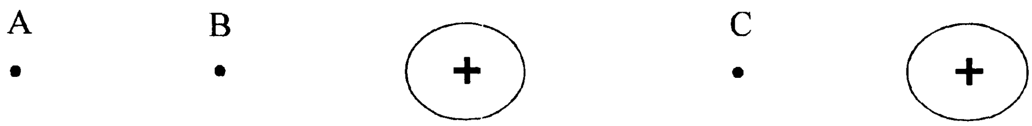

Figure 6.2 Electric field near two positive charges

This question leads out of the same situation as discussed in the previous question, namely, the field between two charges. The series of questions is intended to lead from the students' previous answers about potential into answers about the potential difference and the resultant current. Students' answers to part (i) corresponded without exception to their answers to the previous question. Those answers to part (i) therefore had a confirmatory value relative to the students' answers to the previous question, but do not add any further information.

However, the students' answers to part (ii) are pointers to their understanding of potential in fields as it relates to circuits, and those answers formed the basis for the analysis below.

Students had a range of sophistication in their answers. Many students worked from simple rules about the situation. These students were unable to see the physical principles where field strength and potential difference cause movement of charge, which in turn causes changes in field strength and potential. This is not a simple process, and the feedback involved in it can lead to oscillations and chaotic behaviour, in more complicated physical situations. However, in the situation of the present question, this feedback simply causes the flow of charged particles to stop, after a momentary movement of charge. Only those students working with an abstract model of charge in the formal mode were able to appreciate these effects causing the current to flow briefly and quickly stop.

Concrete symbolic responses

These responses were characterised by an inability to focus on the physical principles which relate to movement of charge in this situation. The responses focussed on application of rules, rather than consideration of the overall structure of principles which should guide this application of rules.

As discussed in the treatment of the last question, students all predicted that minima and maxima in potential would correspond to those in field strength. As a result, their predictions about potential in this case corresponded to those about field strength. In particular, they all said that there would be a potential difference between the points A and B, although not all students used this potential difference in their predictions.

The ten students responding at a unistructural level in the concrete symbolic mode concentrated on a single aspect of the situation to predict the current. In the example below, this was based upon the existence of a closed circuit. This student (s. 54) predicted a potential difference between the points A and B, but no current along the wire between them. The student's answer disregarded this point about potential, focussing solely on the lack of a closed circuit:

> A current will only flow if the entire circuit is closed
> *Interviewer: O.K., so would a current flow?*
> *Student: Only if the current was joined ... but you'd have to join the wire, wholly, or in some way so that the potential could then flow so that you get a flow of electrons, a flow of current as well.*

Other unistructural answers concentrated on the idea that a wire must be moving in a field to produce a current. This is tied up with confusion between electric and magnetic fields. It is also the result of concentration on the superficial appearance of the problem, i.e., a wire in a field. This superficial detail led to the rote response that the wire had to be moving, which students remembered from questions about magnetic fields. The next excerpt provides an example of this other form of unistructural response. Again, this student (s. 4) predicted a potential difference between the points, but did not use this in his answer. In response to questioning about whether there would be a current, he replied:

> Not if it [the wire] were just placed there, if it were moving through the field then yes.
> *Interviewer: Will a current flow?*
> *Student: If it's just put in an electric field and left there, no, but if it's moved through the field, a current would be induced in the wire.*
> *Interviewer: O.K., is there any difference between electric and magnetic field?*
> *Student: [long pause] Stretching my brain now [pause] no, I don't think so.*

The unistructural responses above concentrated on one aspect, such as the completion of a circuit or the need for movement through the field. Those responses did not use the notion of a potential difference between the points A and B. By contrast, the eight students producing multistructural concrete symbolic responses concentrated on the potential difference between points A and B, as well as the idea that potential difference causes current. They did not relate these notions in terms of any other principles. In particular, they did not take into consideration the finite supply of charged particles in the conductors. This led them to say that there is a current in the wire, and that it continues indefinitely. An example of this was given by one student (s. 18), who predicted a current "as A & B are at different potentials, hence current flows". Further, the current would not stop, "as A & B are always at different potentials, unless they move". When asked about this in the interview, she said, "it's at different potentials, so it should flow all the time". This inability to link the ideas of potential difference and current to those of charged particles was characteristic of the multistructural answers.

The four students responding at the relational concrete symbolic level were able to relate the idea of potential difference to charged particles, using the idea of current. However, their understanding was still not sufficiently abstract to explain the effect of the fields of the moving charge, which act to quickly stop the current in the wire.

For example, one student (s. 56) said there would be a current and that "protons from B will flow to A". He said that the current would stop "when all the protons at A are transferred to B". In further questioning, he corrected this to an idea that electrons in the wire would flow from B to A, but still had the idea of "running out of charge". In this response, he connected the potential difference to these ideas about flowing charge. However, the principles which cause the flow of charge to stop well before "running out of charge" were not included in this response. Such detail was only seen in formal mode responses.

Formal responses

By contrast to the concrete symbolic responses, the six students who responded in this mode were able to appreciate the effects which result from the field of the moving charge in the wire. There was an overview in terms of these effects, where the reasoning was in terms of the behaviour of particles, and the effects of these particles on other phenomena. This placed students in a unistructural level of the formal mode, which was all that was required to answer this question. Further cycles of growth might be observed in answers to more involved questions, but this unistructural formal level was observable in the students' responses.

These students were capable of reasoning with the idea of moving charged particles and to tie it to change in potential difference, for example, one student's (s. 24) prediction of potential difference was tied to ideas of current. She predicted a current because, "Current flows from a higher potential to a lower potential as electrons are pulled, by electrostatic attraction toward the + point charge. Current flow is opposite from electron flow, current would flow from B to A". This mention of electron flow is an aspect of this response which was also seen in the relational concrete symbolic example discussed above. What brought this response to a higher mode of understanding was the description of the results caused by the movement of charge, which act to stop the current well before the electrons run out: "If the wire was just between A & B, electrons would flow toward the +ve until the end at A had lost enough to give it a net +ve charge, at which point e^- start to flow toward A until a balance is achieved & the current stops flowing". In the last quote, one can see an understanding of the relationship between charging and field strength, which shows an ability to reason within the model of moving charge and fields. This ability to reason about the effect of the movement of charged particles was missing from responses in the concrete symbolic mode. This point is developed in more detail later in this chapter, as it has bearing on more than potential in fields.

Conclusion about potential in fields, potential difference and circuit phenomena

Students did indeed connect potential in fields to potential difference and current flow, but only the most able used abstract models in this connection. The majority of students applied rules about circuits, without appreciating the more complicated aspects of the problem which cause current to stop flowing in this situation. They were able to mention moving charge, but not able to reason in terms of the effects of this moving charge. They applied simple rules to predict the macroscopic behaviour of the open circuit, e.g., "there will be a current", and then used this to predict the behaviour of the particles. These concrete symbolic responses were not able to describe the effects of charge and used them to predict the behaviour of the phenomenon. This ability to describe the effects of charge movement on the fields causing them to move was characteristic of formal mode understandings of this issue. The concrete symbolic responses did not display an ability to consider the conditions and constraints which govern the movement of charge in fields, and came to premature conclusions based on simple rules. The question next discussed studied whether students could use considerations of potential energy in predicting the movement of charge.

Potential, potential energy and kinetic energy

The previous questions about potential showed that students tend to identify it with field strength and have difficulty relating it in detail to electric current. In the sixth question of test/interview 1, students were asked to use the relationship between potential and energy to predict the motion of a charged particle between the plates of a capacitor. A full treatment of students' responses to this question appears in appendix P. Use of the SOLO Taxonomy for the responses to this question was judged inappropriate, due to the small range of response. Students, in general, simply focussed on one aspect of the question. The question involved two parallel-plate capacitors with the same voltage across them and different spacing between their plates. Students were asked to compare the speeds, upon impact at the positive plate, of electrons released from the negative plate of each capacitor.

In summary, most students' ideas about potential in this situation were based on the idea that potential is identical to field strength, rather than energy. The result of this idea was to cause students to predict that the velocity of the electron is greater in the capacitor with greater spacing between the plates. This logic is based on the idea that "same potential means same field strength means same force on each particle". If one assumes the same force on the electron in each capacitor, it is only logical to predict that the electron accelerating over a greater distance will have a greater velocity. This prediction follows from the assumption that potential is equivalent to field strength.

Only seven of the 28 students were able to use the concept of potential as equivalent to energy, to predict that electrons would have the same velocity in each case. The reasoning behind this correct answer is that the potential across which the electron moves will determine the kinetic energy it gains, which determines its velocity. As the potential is the same for both capacitors, the kinetic energy is the same for both electrons.

Responses to this question showed that students had difficulties relating potential to considerations of work and energy in the case of movement of a single charge in a constant field. These difficulties corresponded to those which they had shown in their considerations of movement of a number of charges in a conductor in the question discussed above. In both cases, there was the same tendency to assume that potential was identical to field strength, rather than using its more complicated relationship to energy.

Overall conclusions about understandings of potential

Students generally had simple ideas about potential. Most of them assumed consistently that it was the same as field strength, across a variety of contexts involving fields, circuits and charged particles. Predictions about maxima and minima of potential in fields corresponded to those made about the maxima and minima of field strength, for all respondents. The relationship between potential and work/energy began to be developed by some of the more able students, but even they were not able to come to a description of the true relationship between potential and field strength which results from this.

In predicting the motion of charged particles, this same confusion between potential and field strength prevented the majority of students from using considerations of kinetic energy. It seemed that potential was too abstract a concept to have meaning for most of these students.

Again, it was possible to identify a number of elements in students' responses about potential, in the context of the given questions. In their responses, the words "field strength", "energy", "work", "movement" and 'voltage' came up, apparently as individual elements of concrete symbolic reasoning. However, the concepts behind these words could also be used as relating features in the concrete symbolic mode, or even as relating principles in the formal mode. This serves to emphasise the point that an analysis using the SOLO Taxonomy cannot be based on a keyword-searching strategy. The word "energy" could be used in the simplest response, while the concept of energy was rarely used, and use of the concept was characteristic of abstract formal mode responses about potential.

UNDERSTANDINGS OF CURRENT AND ITS RELATION TO FIELDS

Current is an important concept in understanding circuit electricity. This section seeks to describe students' ability to relate this concept of current to their ideas about electric fields. It first examines the effect of students' existing ideas about electric circuits on their ideas about fields. Leading out of this is a consideration of students' understandings of the interactions between circuits and fields. This was done by questioning about the situation where an induced electric current is produced. Production of an induced current involves the interaction of both fields and currents, in the context of an electric circuit.

Effects of ideas about circuits on ideas about fields

There were two questions investigating these effects, both in the first test/interview. The first was question 9 of that test/interview, which was aimed at the idea of current consumption in circuits. In particular, it was concerned with whether this idea had effects on the students' predictions of fields due to the current. The second was question 10, which was aimed at students' understandings of the field around a battery. There was especial interest as to whether this field was understood in terms of constant current from a battery. Responses to both these questions are described at length in appendix P. A SOLO analysis of these questions was deemed unprofitable, as the students have concentrated on simple single aspects of the situation in their response, with little variety in responses.

When analysing student responses to the first of these questions (question 9 of test/interview 1), it became apparent that ideas about circuits carried on to affect the students' ideas about fields. This question concerned the magnetic field around various parts of a simple d.c. electric circuit. Ideas about current consumption in a circuit led to predictions that the current, and the magnetic field associated with that current, would decrease as the current moved further away from the battery. This indicated that students' ideas about magnetic fields in this circuit were based on their ideas about current, rather than being the result of separate instruction about fields. The students' misconceptions about circuits added another factor to their misconceptions about fields. A similar result was seen in their discussions of the magnetic field around a battery in the next question.

The second question (question 10 of test/interview 1) concerned whether a battery would have a magnetic field around it while it was out of a circuit. Student predictions about these fields around the battery showed the result of their beliefs about currents in circuits. Many students made the correct prediction that the battery would have no current and hence no field around it. Students who predicted a field around the battery were often confused about the difference between electric and magnetic fields. However, there was the same result as in the preceding question, namely, that students' understandings of aspects of electric circuits, such as current, carried through into their predictions about related fields. Interest in the effects of students' ideas about circuits on their ideas about fields was also an aspect of the investigation of induced current, described below.

Induced current and its relationship to understandings of fields

This issue was treated by a question in several parts, which was question 1 in interview 3, and related to the diagram in figure 6.3 below. The questioning consisted of both written and verbal components. The verbal questions were aimed particularly at students' qualitative understandings of the causes behind the induced current.

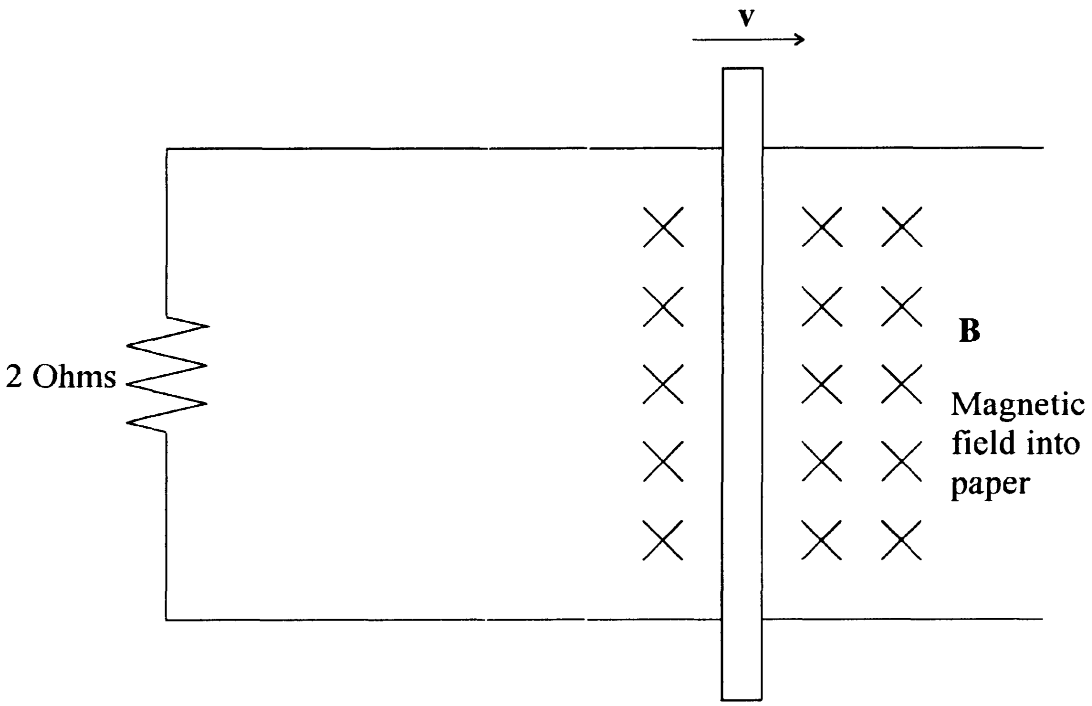

Figure 6.3 Situation causing an induced current

(0) [Written, with diagram (figure 6.3)] The bar (50 cm long) is sliding at a speed of 2 ms^{-1} through a uniform magnetic field of 10^{-4} T. The bar has contacts at each end going through a resistance of 2 ohms as shown. What is the current through the resistance?

(i) Have you seen questions like that before?

(ii) Can you say which way the current will go?

(iii) Why does a current flow?

(iv) Does the current cause any effects of its own?

(v) Can you explain what happens in terms of charges in the bar?

(vi) [Extension written question] (using the same diagram) If the current through the resistance is measured to be 2.5 x 10^{-3} A, and the speed of the bar is known to be between 5 ms^{-1} and 10 ms^{-1}, then what does this tell you about the magnetic field? (The bar is still 50 cm long).

(vii) If the bar is moving through a uniform magnetic field as before, but without contacts, is there a current in the bar? Is there a voltage? Can you explain in terms of charges in the bar?

(viii) Can you explain what happens in terms of changing magnetic flux?

(ix) What happens if you move a wire through a magnetic field? What does this depend on?

The answers to the above parts of the question were analysed separately. Details of results for part (viii) of the question were given in the section of chapter 5 dealing with flux in fields; details for part (vii) above are given in the current section; and details for the remaining parts appear in appendix P. A summary of the results for the various parts of this question is given below, followed by the details of responses to part (vii), which dealt with a non-routine case of electromagnetic induction.

Students' answers to the written question of part (0), which asked for a calculation of current, did not, in general, display complicated reasoning. This showed the same themes as previous responses to other quantitative written questions, as discussed in chapter 4. There was a strong emphasis on remembering equations, and a general failure to use principles to guide the use of these equations. Students were generally unable to answer the routine written question in part (0), and as a result, the extension written question of part (vi) was not relevant to this group of students. This failure to use principles to guide use of equations was investigated further by the verbal questions, which were intended to determine whether the students might understand these principles in some other form.

Students were asked in part (i) whether they had seen such questions before. The majority of students (9 out of 15) replied that they had. However, this familiarity did not appear to have produced a deep understanding of the subject When asked in part (iii) to describe the cause of current, students tended to focus on surface features of the situation, such as the movement of a bar in a magnetic field. Some used field lines in this context, but the majority simply mentioned the movement of the bar. Only a few were able to describe this in terms of particles moving within the bar, and the magnetic field acting on each of these particles. Even when specifically asked to consider particles in part (v) of the question, most students were unable to describe the situation in these terms.

In part (iv), questioning as to the effects of the current indicated that students were not, in general, aware of the principles of energy conservation, or even of Lenz's law, in this context. There was a tendency to suggest a single effect of the current, such as magnetic field, without further explanation. There was no ability to link this to other concepts, such as, the magnetic flux in the circuit, for example. The request for students to link magnetic flux to the situation in part (viii) made it clear that students were unable to do so (this part of the question was discussed in the section of chapter 5 dealing with flux). When asked for a general summary, in part (ix), their responses did not show any overall structure related to principles, rather, they listed some aspects of the situation.

As an example of the students' statements about this topic, details of responses to part (vii) are presented below. This question concerns a non-routine example of electromagnetic induction. As a result of the relatively novel nature of the question, rote-learned responses appear to have been minimised.

If the bar is moving through a uniform magnetic field as before, but without contacts, is there a current in the bar? Is there a voltage? Can you explain in terms of charges in the bar?

The situation in part (vii) above was intended to confront students with something they had never studied before. While the situation appears unrealistic at first glance, it is identical to a metal aeroplane flying through the earth's magnetic field. In any case, the situation presented in question 1, as shown in figure 6.3, is at least as unrealistic, involving as it does a bar moving linearly through a magnetic field along conducting supports. The situation of question 1 was chosen as it was a routine type of physics problem on which to base the further questioning of this interview, and the situation in part (vii) was chosen as a non-routine variation of the same theme.

Students' answers to this non-routine question of part (vii) showed the same patterns of reasoning as for the related questions (discussed in appendix P). The unusual nature of the situation in this case cast students' reasoning in a new light.

Concrete symbolic responses

The two students producing unistructural responses in this mode focussed simply on the idea that a current would flow in the situation, for example, one student (s. 44) responded:

> *Interviewer: Well, if you have a bar moving through a field as before, but without any contacts, is there a current?*
> *Student: Hmm [long pause] I'd say yes, but that'd be a guess. I dunno.*
> *Interviewer: O.K., what would you expect the current to be doing?*
> *Student: Probably just going through the rod or something.*

By contrast, the four students responding multistructurally focussed both on the fact that they expected a current to flow, and on the fact that there was no circuit. There was no integration between these facts, and an example of this can be seen in the response below from one of these students (s. 17):

> *Interviewer: So would you expect a current?*
> *Student: Well [pause] not really, coz it's not contacted to anything, so where does it come and go, [pause] see, you've got to have a flow of current [pause] I don't know [pause] but then you think to yourself - no, I'm not sure.*

Interviewer: What do you think to yourself?
Student: Well, I think to myself, if it's contacted and then there's a flow of current, then why wouldn't there be the potential for it to occur, but coz it's not contacted it's just not being [pause] taken out of the bar, in the magnetic field it's moving in.

The above multistructural response had no relation between the concept of flow of current, expected because the bar was moving in a magnetic field, and the idea that the bar had no contacts. This left the student unable to make a prediction, confused by these conflicting facts. By contrast, the four students producing relational concrete symbolic responses were able to relate the current, the need for a circuit and the charges in the bar. This was done through the linking concept of current, as seen in the next excerpt. At the same time, the student (s. 22) below did not reason primarily in terms of the charged particles in the bar, talking uncertainly about their behaviour only after he had finished talking about current:

Interviewer: If the bar is moving in a uniform magnetic field, as before, but without the contacts, is there a current?
Student: No, there wouldn't be.
Interviewer: Why not?
Student: Because although the um, two ends are at - there's a potential difference between the two ends, there's no um, external circuit for which that can flow through. It's like having a battery without connecting it up to anything.

In the above, the student (s. 22) focussed on the need for a circuit. He was able to relate this to voltage, as can be seen below:

Interviewer: O.K., is there a voltage involved?
Student: Uh, there'll be a voltage distance across the ends there, like, if you hooked them up from either end, at each end, you'd be able to measure a voltage.

This was also related to charges in the bar:

Interviewer: O.K., and what's happening in terms of charges within the bar.
Student: Uh, I dunno.
Interviewer: Could you guess?
Student: I could take a rough guess and say the electrons are being pushed up to the negative end, the free electrons.

The prediction above about the electrons in the bar was uncertain, and seemed to follow from his earlier predictions about the current in the bar. These predictions about the current were not based on reasoning about the electrons. Rather, they resulted from consideration of the macroscopic fact that there the bar was moving in a magnetic field. By contrast, reasoning primarily in terms of the charged particles in the bar was the key feature of the formal mode responses discussed below.

Formal responses

These five students could see that there would be a transient current in the bar, resulting from the effect of the magnetic field on the charged particles in the bar. They saw the effect of the movement of charge, as this creates a field which in turns stops the movement of charge. Their reasoning was based on considerations of moving charged particles, as seen in the below student's (s. 24) comment:

> *Interviewer: O.K., if you have a bar moving through space as before, but without contacts, will there be a current in the bar?*
> *Student: [pause] Um [pause] like, the electrons, like as you start to move the bar, the electrons, will all move down to one end, I'm not sure what end it is, say it's this end. So you'll have lots more electrons here and more positives here. And that - once you get too many electrons here, they'll stop flowing because they'll be, like, the electrons will be repulsed by the overall negative charge here, they just won't flow any more, because there'll be too much of a negative charge, and the positive charge up here'll also be pulling them back.*

Here, the student considered the behaviour of the charged particles in the bar, and the results when these charged particles move. His predictions were based on his consideration of this system of charged particles. There are similarities between the factors that have to be considered in this question and those which had to be considered in the question (question 4 of test/interview 1), previously discussed in this chapter, about a single wire in an electric field. In both questions, students have to see that charges will move in the conductors, and that the movement of these charges creates an electric field which acts to stop further movement. In a range of questions, most students reasoned about the cause of current on the basis of simple rules. Only a few students reasoned from the basis of a particle model in order to explain the current, and to predict the effects in this novel situation. This indicated that the particle model was inaccessible to most of these students.

Conclusion about students' understandings of current as it relates to fields

Students' ideas about current both influenced and were influenced by their ideas about fields. Their responses about the induction of current in magnetic fields were generally based upon simple rules, which did not involve a consideration of the particles making up this current. These simple rules formed unitary elements of concrete symbolic reasoning, being propositions of the kind: "a current needs a closed circuit", "movement in a field causes a current", "a potential difference causes a current", "a current is made out of particles". Some students were able to relate these rules to one another, but were unable to use principles to guide their predictions. They also had only a limited ability to relate this to the concepts of potential, as discussed in the previous section of this chapter. The next section of this chapter takes up the issue of students' undestandings of charged particles in connection to electric fields and circuits.

UNDERSTANDINGS OF PARTICLES AND MACROSCOPIC PHENOMENA

Students generally had trouble applying the idea of invisible charged particles to their explanations of macroscopic, observable phenomena. While students were able to mention these charged particles, their responses seemed to be based on consideration of simple rules. These rules were centred on concrete macroscopic phenomena. It was rare for students to be able to reason from consideration of particles to make complicated predictions about macroscopic phenomena. Rather, their mention of particles was dominated by their earlier reasoning about the macroscopic phenomena. There appears to be a high degree of abstraction needed to reason using this particle model.

Both the previous sections of this chapter have that shown that students have difficulty relating particles to macroscopic situations. The students may have mentioned particles in their responses, but particles did not, in general, play a significant part in the reasoning leading to those responses. When considering the movement of charges in open circuits, students generally applied simple rules to make their predictions about current, and only then considered what these predictions would imply for movement of particles. Very few students made predictions by reasoning from the behaviour of the particles to predict the existence or otherwise of a current. Completing the picture of students' use of charged particles in reasoning, which has come from other questions discussed in this chapter, student responses to another question are given here. This question was concerned with students' ability to integrate the ideas of force on a charged particle, force on a current, and induction of current all caused by motion in a magnetic field. This integration is essential for reasoning about electromagnetic induction by using a particle-based model of electricity.

Relation of moving particles to currents moving in magnetic fields

The following question was question 5 of interview 3.

How would you predict the direction of force on a charged particle moving in a magnetic field? How would you predict the direction of a current caused by moving a wire in a *magnetic field? How would you predict the direction of force on a wire carrying a current in a magnetic field? Is there any connection between these?*

Students commonly have a need to predict directions of forces and currents in their assessment questions on this topic. The three cases mentioned in the above question can all be predicted by use of separate rules. However, it is also possible to make these predictions by seeing the similar principle underlying the three cases, and applying the same rule in all cases. This use of a principle to provide structure and reduce memorisation was the focus of this question.

<u>Concrete symbolic responses</u>

No unistructural responses were observed for this question. A reason for this was in the nature of this question, which asked students specifically about a number of rules. The nine students producing multistructural concrete symbolic responses gave a number of "hand rules", but provided no evidence of a connection between them. These rules were the unrelated elements in their reasoning. In the following dialogue, one student (s. 1) described a situation where a current is induced by moving a wire in a magnetic field:

> *Interviewer: O.K., so how can you say which way the current would go in that?*
> *Student: [pause] Using the right hand rules, I would imagine [pause] you've got, magnetic field's going into the page [pause] from this one, [pause] it would be b i cross l, so it'll be a uh, cross product, the right hand rule, the magnetic field's going down, then the length is going like that, the current.*

This student used the idea of a "right hand rule" to predict the direction of current. He used a similar means to predict the direction of a charged particle moving in a magnetic field of given direction:

> *Student: [pause] The thumb is the magnetic field, so the force'd probably be [pause] that's a bit harder, that one. I could take a guess at it, but [pause] the force would cause it to move into the page, circle [pause] into the page [pause] so the charge going like that, circle like that.*

Next, the student was asked to predict the force on a current in a magnetic field.

> *Interviewer: Have you talked about trying to predict the direction of force on a wire carrying a current through a magnetic field?*
> *Student: [pause] No.*
> *Interviewer: O.K., so how do you predict that?*

Student: The force [pause] on a wire [pause] due to the current in the magnetic field [pause] I'm sure it would be by just rearranging some equations [pause] to make [pause] if you're doing it by equations, you'd just have to rearrange them.

...

Interviewer: Say that you're only interested in the direction.

Student: Right hand rule [pause] but again I don't know what it is, because it'd be [pause] the flat hand.

In the above interview transcript, the student mentioned another rule, this time using the flat hand. Following this, the student was asked to relate the "right hand rules" he had mentioned before:

Interviewer: O.K., how many versions are there of the right hand rule?

Student: Here I've learnt [pause] two, I think. In high school I must have learnt about six or seven of them [pause]

Interviewer: O.K., and what's the important difference - how can they all be right?

Student: They're different [pause] um, depending - I learnt in high school different right hand rule for every equation that I learnt [pause] I didn't actually learn them, I was told about them, I couldn't actually learn them because there was too many.

Here, the student admitted that he viewed the situation through a multiplicity of "right hand rules", which did not fit together in his mind at all. This feature adds further support to the independent nature of elements concerning the direction of effects in the students' understanding.

In the three relational responses in the concrete symbolic mode, there was a similar profusion of right hand rules, but the difference from the case above was that they were integrated in terms of a rule for applications. In the first part of his answer to this question, a student (s. 17) showed the ability to predict the direction of force on a charge:

Interviewer: How do you predict the direction of the force a charged particle that's moving in a magnetic field?

Student: [pause] The force is f equals q v b [pause] just work out the force from there [pause]

Interviewer: O.K., what if you want to know the direction of the force?

Student: Oh [pause] this is f, this is b, and [pause] this is v [shows fingers on hand]

Further questioning related to the above showed that the student was using his right hand with the thumb as force, the index finger (pointing forwards) as velocity and the middle finger (pointed outwards from palm) as magnetic field. This arrangement gives a correct result for direction of the force. Following this, the student (s. 17) was asked about the force on a wire carrying a current:

> *Interviewer: ... what about if you've got a wire carrying a current through a magnetic field, is there any force on that?*
> *Student: Yeah [pause] yeah, the motor effect. There's a force on the wire, and that's [pause] f equals b i l.*
> *Interviewer: O.K., what about the direction of the force?*
> *Student: The force on the wire?*
> *Interviewer: Yeah.*
> ...
> *Student: That's force, thumb's force, middle finger's magnetic field, and the other finger's current. So if the current's that, and the magnetic field's that way, then that's force again.*

This statement concerning directions corresponds to the one made previously in reference to the moving particle in the magnetic field, and is also correct. It is still not clear whether this student has any means of relating the two previous predictions. However, in the next excerpt below, it becomes evident that the student was relating those predictions, and was able to relate them to the direction of an induced electric current:

> *Interviewer: ... If there's a wire moving through a magnetic field, does that cause a current in the wire?*
> ...
> *Student: [pause] Isn't it the same rule again? [pause] Like, um, that's force, that's magnetic field [pause] I remember - the thumb's force, the middle finger's magnetic field and the other finger's the other thing - he said we could always use that [pause] but here, there's no force, except there's a velocity, so that must have a force causing it, so thumb's velocity, middle finger's magnetic field, and so the pointing finger must be current.*

In the above, the student related the rule for direction of an induced current to the earlier predictions of direction of force on particles and current. He said "Isn't it the same rule again?", and suggested that the thumb would be the force and the middle finger the magnetic field, in all situations. In this case, this approach gives an inaccurate result, but this was not discussed in the interview. When he was asked to further discuss the relationship between the situations, he stated a rule which he applied to all of them:

> *Interviewer: O.K., you've talked about the direction of the force on a charge moving in a magnetic field and about the direction of the force on a current moving in a*

magnetic field, and about the direction of a current from moving a wire in a magnetic field. Now, is there anything in common for all those things?
Student: They're all direction [pause] yeah, I think you use the same rule for all of them. Like [pause] thumb's force, middle finger's magnetic field, and the pointing finger's the other thing, like current.

The above is a clear description of a rule linking the prediction of direction for all the situations discussed above. However, as could be seen in his prediction of the direction of an induced current, his relationship between these situations was not sufficient to allow an accurate response in all cases. The relationship he used was a simple rule, with the same variables being assigned to the same fingers in each case. It seems possible that he may have seen this somewhere before, perhaps in high school. There was no abstract linking between the rules, through consideration of the microscopic charge movement responsible for macroscopic phenomena. This form of connection only began to be made by students responding in the formal mode.

<u>Formal responses</u>

The three formal responses were able to relate the rules describing particles to the rules describing current by considering the existence of the charged particles making up the current. These charged particles were an integral part of the students' reasoning, rather than being a consideration only after the students had made their predictions. In the response below, the student (s. 52) was describing the direction of an induced current, and, spontaneously, used the concept of electrons to deduce this direction:

Interviewer: O.K., you said something about v cross b, so how does that tell you the direction?
Student: Finger rule, we learnt it, you know, have to do it ... that gives you the direction of the force, that is acted upon that charge, on the electron.
Interviewer: O.K., so you said that something will move in the direction of those arrows there?
Student: The current will move in the direction of the arrows, so it'll be [pause] oh, wait a minute [pause] oh, that's hard, coz see, the current's not really the electrons, it's the opposite. It's the electrons [pause] the velocity [pause] that way, the force acting upon that charge is that way [pause] so [pause] so the current'll be going the other way.

In the above, the student has explained the direction of current in terms of forces on electrons in the bar. He then used this model of electrons to predict the current. He also makes a distinction between electron current and conventional current. His use of particles in the above situation is consistent with his description below of how to predict force on a charge:

Interviewer: O.K., and how do you predict the direction of the force on a charge?
Student: With, what do you call it, um, left hand rule [shows left hand with fingers at angles].
Interviewer: O.K., and what do each of the fingers mean there?
Student: Oh, index finger is v, the [pause] third finger is the direction of the magnetic field [pause] and the thumb is which way the force is going to be, so um, if it's going [pause] clockwise, it's v [pause] b [pause].

This is accurate. However, when asked, below, how to predict the direction of an induced current, he spontaneously used these ideas about the force on the electrons making up the current.

Interviewer: O.K., how would you predict the direction of a current caused by moving a wire through a magnetic field?
Student: Um, the same, but um, v [pause] hey [pause] the same way, but the force now refers to the [pause] electron, I think [pause] ooh, I might have been wrong in the first one, I'll have to read it up ... Because I can't remember if the finger rule applies to the force on the electron or the force on the proton [pause] the proton doesn't move.

The student identified a relationship, in the above, between the direction of current induced by moving a wire in a field and the direction of force on an electron moving in that field. This connection between the two situations is specifically probed below:

Interviewer: O.K., so how does that force on the electron relate to the direction of the current?
Student: If the force from the left hand rule refers to the electron, then the current goes in the opposite direction. But if it refers to the charge on the proton, the force on the proton, it'll go in the same direction as the force.

As can be seen from this response, the student was reasoning in terms of the particles making up the current, and predicting the current from there. His uncertainty about whether the particles involved are protons or electrons led to uncertainty about the direction of the current. This shows clearly that the particles are the primary concern in his reasoning. To finish this consideration, he was asked to predict the direction of force on a current in a magnetic field, and to relate all the three cases:

Interviewer: O.K., and finally, how would you predict the direction of the force on a wire that was carrying a current through a magnetic field?
Student: [pause] If, if the force equals i l cross b, or l i cross b, which I think it does, then in the same way as the left hand rule.
...
Interviewer: So is there any logical connection between the force on the electron and the force on the current moving through the magnetic field?
Student: It's the force on the proton, earlier on, not the force on the [pause] if we're going to use the left hand rule with the current, then anything experienced - like, it's all going to be - of course it's current, coz all these rules apply to a point positive charge, a test positive charge.

The student, in the above response, has unified all the three rules in terms of the force on a "test positive charge". This consideration allows the use of a single rule to describe all situations, by considering the behaviour of the charged particles in that situation. This added abstraction makes it possible for the student to avoid the memorisation of a number of separate rules. Described in terms of the SOLO Taxonomy, these separate rules were unistructural elements, and the abstraction allowed by consideration of the charged particle model has allowed the student to place the rules into a coherent system. However, few students were able to use this abstract consideration of particles in their responses, indicating that consideration of charged particles is not a useful means of unifying responses for the majority of students.

Conclusion about students' ability to relate particles to macroscopic phenomena

In this section, as well as the preceding sections of this chapter, students' responses have generally failed to use particles in their reasoning, although particles were often mentioned. This failure seems to be the result of the abstract nature of the particle model, which presents conceptual difficulties for students. Students were able to produce unistructural concrete elements, such as, the idea that "current is made out of particles", or that "there are particles in conductors". However, they displayed, in general, an inablity to reason with a charged particle model. Students' reasoning was more commonly based on rules about whether current should, or should not, flow in a given situation. After application of these rules, students were then able to say, as a result of those predictions, that the particles would behave in a certain way. However, few students reasoned from the behaviour of the particles in a given situation, in order to predict the macroscopic behaviour of the situation. There was an emphasis on the use of simple rules for predicting macroscopic behaviour directly. It would be interesting to see if different emphases in the teaching approach for this subject could affect the nature of this problem, perhaps by de-emphasising the particle model.

CONCLUSION ABOUT AND IMPLICATIONS FOR PHENOMENA RELATED TO FIELDS

As seen in the previous chapter, students tend to have concrete and simplistic ideas about representations of fields. In this chapter, that tendency was also identified with respect to their ideas about phenomena related to fields. Overall, for the students in this study, qualitative understandings of concepts were poorly developed.

Their understanding of potential, a concept linking fields to circuits, was generally poorly defined. It was linked to students' ideas of field strength, with potential and field strength being identified as synonymous in students' minds. This was an almost universal occurrence in the study, as field strength seems to be a far less abstract idea than potential, the latter requiring ideas of work/energy to be meaningful.

In keeping with this limited understanding of potential, students had difficulty reasoning about currents caused by field phenomena. They generally operated on the basis of simple rules of thumb in dealing with these currents, rather than working from abstract principles involving movement of charged particles. There was a clear preference, among students, to remember a number of rules rather than integrate them in terms of overall principles.

Students generally were unable to reason using a model of charged particles to explain field-related circuit phenomena. This was seen in terms of their understandings of both current and potential. It seems possible that an approach which was not heavily based on abstract particles might be more successful, but such a question is beyond the scope of this thesis. Overall, students' qualitative understanding of the charged particle model, like their understandings of other phenomena related to fields, appeared to be at a low level.

By use of the SOLO Taxonomy, it was possible to identify a number of elements in students' reasoning. While the elements used were, to some extent, related to the context of the questions asked, they still have value as a means of describing the structure of students' understandings of the topic. In responses to questions about potential, students produced responses containing keywords as unistructural concrete elements, such words as "field strength", "energy", "work", "potential difference" or "voltage". Some students were able to relate issues together by responses centred on field strength and its relation to other elements in the concrete symbolic mode. Few were able to achieve formal mode responses by using the unifying abstract concept of energy. In answers to questions involving current, students applied unistructural concrete symbolic rules like "the circuit must be closed", "there must be movement of the wire", "a potential difference causes a current". While they could often achieve relational responses, by combining these rules, students were, in general, unable to reason about currents by using a charged particle model. They could produce unistructural statements about charged particles, e.g., "a current is made out of charged particles", "conductors contain electrons". They were also able to relate these statements in terms of their ideas about current. As a rule, however, students were unable to use considerations of forces on charged particles and forces resulting from the movement of charged particles. This use of the charged particle model forms an abstract, formal-mode means of describing current-related phenomena. The majority of these tertiary students were incapable of describing given situations in terms of that model, which formed the basis for their instruction in this area.

This finding of poor qualitative understanding among tertiary students of physics is worthy of some discussion. It corresponds to the findings of a large quantity of research about students' understandings of various topic areas in science. The nature of that body of research, with its emphasis on students' qualitative conceptions, was discussed at length in chapter 2. In brief, the literature contains a large number of publications with findings similar to that of White and Gunstone (1981), who described a poor qualitative understanding of gravity by university physics students. These findings, both in the literature and in the present survey, have a number of implications for educators. This compartmentalisation of knowledge can be addressed by making contact with students' existing knowledge while teaching, and encouraging students to build understanding based on that existing knowledge. Compartmentalisation of knowledge is the logical result of teaching quantitative equations without reference to students' existing qualitative concepts. These implications follow from the lack of qualitative understanding observed among these high-level students.

This can also be expressed in terms of the SOLO Taxonomy. The quantitative material which is taught in the course is primarily in the formal mode of this taxonomy, being of an abstract nature. However, students' responses to the qualitative questions of this survey were primarily in the concrete symbolic mode, being based in simple aspects of the given situation. Students of this age, having completed the pre-requisites required for entry to this university course, would be expected to be capable of reasoning in the formal mode. Their widespread failure to do so seems likely to result from an inability to relate to the abstract course material. In terms of the SOLO Taxonomy, one would suggest that the students' existing levels of understanding have to be the basis for further instruction. If instruction is based on abstractions from the formal mode, as in the course which these students were undergoing, then the students have no way to relate this to their existing (concrete symbolic) understandings. The students have to be brought through the levels, starting from their initial level. The result of giving formal mode instruction to these students can be seen in their responses, as discussed in the last chapter. They attempted to cope with the instruction by remembering simple rules, which can be described as concrete symbolic within the Taxonomy. The next chapter pays particular attention to this general issue of concrete symbolic as opposed to abstract responses, in the context of an in-depth study of individual students.

Chapter 7

IN-DEPTH STUDIES OF TWO INDIVIDUAL STUDENTS*

The previous three chapters considered students' responses to the separate questions in the instruments. Chapter 4 dealt with students' quantitative use of equations, chapter 5 with students' use of field representation and chapter 6 with their understanding of phenomena related to fields. Those chapters have served to give useful insights into students' understandings of various concepts in this topic area. However, it is desirable to know still more about the way the concepts, addressed in those chapters, relate to one another.

The current chapter achieves this by looking in detail at the responses of two students in turn. The responses from each of the students are examined using the same structure as was used for the analysis of the whole group in the three preceding chapters. There are comments on their ability to use equations quantitatively, followed by comments on their use of field representation and the result of this for their understanding of phenomena related to fields. At the end of this chapter, there is a comparison of the two students, and a discussion of the implications of this comparison.

The two students described here were chosen as follows. Conrad's (this is not the student's (s. 56) real name) responses were such that he was roughly in the middle, in terms of ability, of the class studied. This meant that knowledge gained from studying him would be widely applicable to this class. His responses tended towards the concrete symbolic mode of the SOLO Taxonomy. The other student, Forrest, (this is also not the student's (s. 32) real name) was among the top achievers in his responses. An overview of his responses provides a chance to study relatively high-level reasoning. His responses tended towards the formal mode of the Taxonomy.

CONRAD

Conrad's understanding of the topic was typical of the class surveyed. This was the case for his test scores, where he scored 17/40 for the mid-semester topic test on electromagnetism compared to the class average of 15.7/40, and 44% on the year-end test compared to the

* Results presented in this chapter have already been the subject of a publication: Guth, J. (1995). An in-depth study of two individual students' understanding of electric and magnetic fields. Research in Science Education, **25**(4), pp. 479-490

class average of 47.7%. His scores on these tests indicate that his ability to manipulate quantitative equations was poor, but representative of the class surveyed. Inspection of his answers to quantitative questions indicated that there was little evidence of principles being used. His qualitative understandings of the topic were similarly representative of the class.

In overview, Conrad's grasp of field representation was poorly developed, as will be elucidated at length below. He had a strong reliance on field lines to explain interactions between fields, and was unable to grasp the abstract notion of potential in fields. There was a distinction in his mind between electric and magnetic fields, although the exact difference between the two was not clear in his responses. Overall, his ideas of field representation were not completely developed, with a number of concepts still indistinct.

This concrete symbolic grasp of field representation had implications for Conrad's understanding of phenomena related to fields. His predictions of particle movement in fields were accordingly affected, with a strong reliance on field lines. Similarly, his reasoning about phenomena occurring in open electric circuits was based on simple rules, rather than consideration of the particles and fields in these circuits. Answers tended strongly towards the concrete symbolic mode of response, both in describing representation of fields and explaining related phenomena. He lacked a broad overview of the topic.

Conrad's use of equations

Conrad's use of equations was assessed from his answers to the coursework tests. These tests appear in appendices I and J, and discussion of the whole class's responses to them is the subject of chapter 4. His performance was typical of the class, and a number of common themes from the responses appeared in Conrad's work.

He showed considerably more ability to cite equations and substitute numbers into them than ability to manipulate these equations following principles of physics. His work exemplified the common tendency to use equations which were inappropriate to the situation involved. This included the use of equations describing a radial electric field for cases where the field was constant. His poor ability to do non-routine manipulation on equations was indicated by his attempts to prove that the electric field in a parallel-plate capacitor was given by $E = V / d$, where V is the voltage across the plates and d is the distance between them. In this case, he wrote down an inappropriate equation describing radial fields, as well as the equation $V = E d$. However, he did not make the simple step from $V = E d$ to $E = V / d$. This would appear to reflect an inability to pursue the steps of a non-routine proof.

However, he was able to carry through the steps of routine algorithms, such as in his response about balance of forces on a charged particle in an electric field. This response showed an ability to carry through a lengthy calculation with no errors. However, his responses demonstrated no ability to create algorithms based on consideration of principles. This difficulty with use of principles was seen in the majority of students, and was also seen in Conrad's responses to more qualitative questions, discussed below.

Conrad's representation of fields

Conrad's ideas of field representation were based on a concrete symbolic picture of "field lines". These lines were conceived in terms of directly observable entities such as paths of particles, or areas of strength of the magnetic field. In chapter 5, this form of field representation was seen to be a common understanding of the topic. Coupled with this reliance on field lines, his ideas of the field vector and its expression in terms of field strength at a point were not fully developed. Field strength was confused with potential in the field, and the student was not able to reason quantitatively about field strength at a point and its effect on a charge. Conrad's difficulty with vector field was also seen in chapter 5 to be typical of the class sampled.

This student identified field lines with direct observables, in all the given situations. In the context of the behaviour of iron filings near a magnet, he saw concrete lines in the magnetic field as being responsible for the pattern seen. As the student said in the interview, filings form the pattern "because that's where the field lines are ... they just gather together along the field lines". The student's picture of interactions between fields was also dominated by field lines. The quote below refers to a situation where two charges are producing an electric field.

> *Interviewer: O.K., what about where field strength would be a maximum?*
> *Student: A maximum [pause] the field strength [long pause] It'd have to be in between here somewhere. [at an equal distance from the two positive charges creating the field]*
> *Interviewer: Why?*
> *Student: Coz there's two sort of electric fields combining.*

In the above, one sees that the student's ideas of interactions between fields were based on a vague intuitive picture of "combining", with strengths of fields simply adding together.

> *Interviewer: O.K., how would you work out where it was?*
> *Student: [pause] Just by the field lines or something.*
> *Interviewer: The field lines?*

Student: Where the field lines are most concentrated or something.
Interviewer: How would you work that out?
Student: Dunno.

Again, the field lines are paramount in the above, and, as a result, the student was unable to make any specific predictions. Related to this reliance on field lines was a difficulty with using the field vector. As was mentioned in chapter 5, use of the field strength vector was difficult for most students, but essential to an understanding of the abstract system of field representation. This student had some ability to work with the field strength vector, but this reasoning was dominated by concern with the mechanics of manipulation rather than the underlying concepts behind the manipulation:

Interviewer: Can you use vectors to represent electric fields?
Student: [pause] Yep.
Interviewer: How?
Student: By [pause] drawing their components.
Interviewer: Could you sort of show what you mean by that?
Student: Just say that was a positive - no, that was just a - some kind of charge. And you put a positive test charge in [pause] and you're trying to test the electric field with that [pause] and that was positive, just say that was positive, it'd be repelled, so it'd go that way. Like, that'll be the x value and y value, go that way.
Interviewer: O.K., why would you want to use those x and y values?
Student: Oh, coz you get the resultant.
Interviewer: Isn't that what you started with?
Student: [pause] Oh, yeah, you can just use that.

In the above, the student was drawing components relative to an arbitrary axis. While this operation is relevant to the mechanics of calculating using vectors, he still missed the more abstract points about the reasons for using vectors, such as, the representation of fields at all points, and their use in considering the superposition of fields. Although he did consider the field effect on a test charge at a point in the above, there was a concrete symbolic emphasis on the mechanics involved in finding components.

However, when encouraged by prompting, the student was indeed able to relate the field vector to field lines, in a way associated with the formal mode of the SOLO Taxonomy.

Interviewer: O.K., could you use vectors to say something about what the electric field will be in the area all around the two charges?
Student: [pause] Like, you'd have to put like a - you'd have to put a test charge somewhere and then [pause] figure out the electric field from that.

He then drew a test charge at a point, and vectors representing the force on that test charge from each of the two charges creating the field. When asked, in further prompting, to relate this to field lines, he decided that the force on the charge would be parallel to the field lines. Asked if he could draw field lines from this, he said that was an "interesting" idea, and proceeded to draw a field line, suggesting that the force at a number of points on it could be found by the test charge technique described in the above excerpt. This link between field lines and field vectors appeared only after considerable questioning, which led the student in that direction. This indicates that the level of response about these issues is not a result of students' personal inherent limitations, and that it is possible to improve a student's level of response about these topics of field lines, field vectors and field strength.

For Conrad, the concept of field strength was not clearly separated from the concept of potential in a field, and he predicted that the minima and maxima of field strength would correspond with those of potential. He was highly representative of the class in this regard. While the student was unable to connect potential with energy considerations in problems involving them, he was able to give a reasonable description of the meaning of potential in a field:

> *Interviewer: [referring to a written response] You said the potential would be a minimum at point A.*
> *Student: That was just a wild guess.*
> *Interviewer: O.K., have you got any idea what potential is?*
> *Student: [long pause] The um [pause] the work done per unit charge?*
> *Interviewer: And what does that mean?*
> *Student: The [pause] the amount like [pause] just say a proton goes to somewhere um negatively charged or something, the amount of potential energy times the charge.*
> *Interviewer: [repeating parts of last response] "If it goes ... the amount of potential energy", so what do you mean by potential energy?*
> *Student: [pause] Potential it has to do energy. Or the amount of kinetic energy it uses up going from where it is to somewhere else, times the charge.*

In spite of the plausibility of the above description, Conrad was unable to use the concept of potential and relate it to kinetic energy in the context of particles moving in fields. He could describe potential, as in the above, but he was unable to use the concept of potential as a tool in problem solving. This indicates that he was aware of the concrete symbolic definition, but there was no connection to the rest of his knowledge.

As part of his general difficulty with representation of fields, this student had a confused understanding of the difference between electric and magnetic fields. The following dialogue is characteristic of the student's answers to questions and problems involving distinction between electric and magnetic fields:

Interviewer: What is the difference between an electric and a magnetic field?
Student: [pause] An electric field's like a field in which charges move [pause] and a magnetic field's [long pause]
Interviewer: Do you think there is any difference?
Student: Yeah, I'm just not sure what.
Interviewer: So can you suggest any difference?
Student: [pause] Yeah, magnetic - no [pause] not sure.
Interviewer: Would you expect them to have the same effect on everything?
Student: The magnetic field and the electric field?
Interviewer: Yeah.
Student: [pause] Yeah, coz they've got different direction.

This last comment about "yeah, coz they've got different direction" seems to refer to the student's belief that the magnetic and electric fields are mutually dependent, and that their effects are therefore the same in all cases, as they appear together. It is probable that this confusion between electric and magnetic fields seems likely to make it impossible for the student to appreciate the scientist's picture of induced currents, where both electric and magnetic fields are involved.

Overall, this student's representation of fields was based on an attempt to hold things together by concrete symbolic rules, rather than come to a full formal-mode overview of the system of field representation in physics. While prompting did produce some statements about field vectors which were indicative of understandings in the formal mode, these were not representative of the student's responses. He did not spontaneously come to such formal understandings, tending to produce unsystematic rules to answer questions. This piecemeal approach, characteristic of the class surveyed, had implications for Conrad's understandings of phenomena related to fields

Conrad's understanding of related phenomena

Related to the unsystematic representation of fields was a corresponding difficulty with predictions about phenomena resulting from fields. This was visible in a number of areas, which had been highlighted in the study of the class' understanding of these phenomena in chapter 6. Particle movement in fields was poorly understood for reasons arising directly from difficulties with field representation. Predicted trajectories of single particles reflected excessive reliance on field lines and poor understanding of the difference between electric and magnetic fields. Predicted movement of a bulk of charged particles in conductors ignored the fields of the moving charged particles themselves. A causality can be seen from the nature of the field representations to the nature of predictions about related phenomena.

In predictions about single particles moving in fields, field lines again dominated thinking for this student. There was a firm belief that charged particles would follow field lines exactly in an electric field. This belief was resistant to an argument which used the direction of force in this situation to show that the particle could not follow this line exactly. Although not strictly accurate, the belief that particle trajectories follow field lines exactly was very common among the students surveyed. Like the majority of students, Conrad was also unable to relate voltage, potential and kinetic energy in an electric field, when presented with problems which required this connection to predict particle movement.

For particles in a magnetic field, problems arose from the confusion between electric and magnetic fields in the student's mind. In one case, he predicted that the effect of a magnetic field on a particle would be exactly the same as if it had been an electric field. Although he was able to apply the rule for force on a particle in a magnetic field when this was presented in a stereotyped question, he had difficulty applying the rule in a novel situation involving particle movement near magnets. Movement of individual charges in fields presented problems for this student.

The issues surrounding movement of a bulk of charges were also unclear for this student. While he could talk about particles moving in electric circuits, the particle picture appeared to be used only after his initial decision about what would happen in the circuits. His reasoning, like that of the majority of the class, was not based on particles in this case. This was true whether the currents were caused by electric fields, or by induction of current due to movement in magnetic fields.

> *Interviewer: O.K., why do you know there is a current?*
> *Student: Because it's induced by the magnetic field [long pause] I can't remember, something to do with induction or something.*

His ideas about the causation of current, as seen above, were poorly defined. Particles played no role in his ideas about the cause of current, only being considered later, when this was specifically requested, as seen in the quote below:

> *Interviewer: O.K., can you explain what happens in terms of charges moving through the circuit?*
> *Student: What, you mean how they move?*

Interviewer: Yeah.

Student: [long pause]

Interviewer: O.K., can you say that this happens because the charges are doing this and that?

Student: [pause] What happens?

Interviewer: Well, whatever things you observe, like a current flow or [pause]?

Student: Well, like induced by the magnetic field, the current.

Interviewer: So can you relate that to little charges?

Student: Well, the little positive charges go like this.

Interviewer: O.K., and why do they do that?

Student: [pause] Coz that's where the current goes.

Interviewer: O.K., what's actually causing them to do that?

Student: Uh [pause] that rod moving through the - coz that makes a circuit, and coz it moves [pause] through the magnetic field, that gets induced, so electrons [pause] I dunno.

Where a transient current in an open circuit was involved, this student predicted that current would flow until the particles run out. This prediction failed to allow for the effect of the fields of the moving charge. In fact, when the charge moves, it creates a field as a result of its new position, and this acts to stop further movement of charge. The student has failed to grasp this idea. As with the idea of potential, discussed above, he was able to describe charged particles in the circuit, but he was not able to use this idea as a tool for making predictions. He has not appreciated the constraints on the movement of the particles which result from their own effect on the situation. This ability to see the results of predicted changes is typical of a formal mode overview of the topic, as seen in Forrest's responses later in this chapter.

Overall comments on Conrad

The general level of response for this student was in the concrete symbolic SOLO mode. There was a lack of overview in his use of concepts, and each of the ideas was somewhat compartmentalised in his mind. This was evident in responses to both qualitative and quantitative questions. His grasp of field representation was based on concrete concepts, primarily field lines. Associated with this reliance on field lines, the student was unable to reason using the field vector, which is an abstract concept involving association of a vector with each point in space. While he could be led to use the field vector by specifically mentioning it and asking for its use, he did not simultaneously use it as a tool in problem solving. This inability to use the field vector made it impossible for the student to appreciate the abstract concepts which depend on the field vector for understanding, in particular, flux and potential. The nature of Conrad's representation of fields had implications for his explanations of related phenomena.

The inability to use the abstract concepts of field vector and potential led to difficulties in explaining phenomena involving movement of charge in conductors. The student was unable to explain these phenomena in terms of the effects of the moving charge, rather, relying on a set of rules. While he did mention particle-based models, they were ineffective without the underpinning of an abstract representation of electric fields. As Conrad was such a typical student, this pattern of response leads to a number of implications for teaching and learning about the subject area.

Conrad's difficulty with abstract understandings of field representation caused him to make inaccurate predictions about phenemena involving moving charge. Although he did use a particle based model in connection with these problems, it was not possible for him to make effective predictions due to his simplistic representation of fields. This implies that helping students to a more abstract representation of fields is essential if they are to be able to fully explain related phenomena. In the next student, Forrest, one sees a more abstract representation of fields leading to a more effective explanation of phenomena.

FORREST

Forrest was an able student, and this can be seen in his test scores. He scored 29/40 for the mid-semester topic test on electromagnetism compared to the class average of 15.7/40, and 75% on the year-end test compared to the class average of 47.7%. Examination of his quantitative responses indicated an ability to improvise equations based on understandings of the principles involved.

This student tended strongly towards the formal mode of explanation in his test and interviews. His ideas of field representation were clearer, and there was a thorough attempt to fit concepts into a coherent system within his mind. There was a concern with consistency and overview in his answers that was lacking in Conrad's responses.

Forrest's use of equations

Forrest's use of equations was evaluated by studying his responses to the same coursework tests as were the source of data for the evaluation of Conrad. Contrasting his responses with Conrad's, a striking difference can be observed. Forrest, unlike the majority of the class, demonstrated an ability to use principles to guide his manipulation of equations. He was able to complete proofs using this ability.

Asked to prove a result regarding torque on a coil in a magnetic field, Forrest was able to do so, starting from first principles, rather than assuming equations. This was also seen in his response to a question asking for proof of a complicated result about the electric field of a charged disk. His working in these proofs started from relevant equations, and followed rigorous steps to reach the required equation. This required an overview of the system of equations which was lacking for the majority of students. The use of principles demonstrated in answers to these quantitative questions was also seen in his qualitative representation of fields.

Forrest's representation of fields

This student was able to construct a consistent picture of field representations in his mind, which was characterised by an ability to see things in abstract terms. Field lines were part of this student's mental picture, but they were seen in light of their formal definitions, and were divorced from any need for directly observable objects. It is useful to compare his response about the lines in iron filings around a magnet to that of Conrad above. The quote below, relating to that situation, is a relational formal response in SOLO terms, and was used as an illustration of this in the section of chapter 5 dealing with field lines in iron filings.

> *Student: ... if you have a north pole on its own, with no south pole to the magnet, then it will act in a magnetic field as a proton would in an electric field. And by following the path of that pole, you'd be able to see the direction of the lines ... the initial direction of its motion would be a tangent ... if it does have mass then its initial direction is the direction of the field at that point. So if you were to place it a little further along in that direction, but once again with no inertia so it's not already moving, then each place that you put it, it will move off in the direction of the magnetic field and so you could trace out a field line ...*

In this response, the student made a distinction between field lines and the trajectories followed by particles in a field. This distinction also appeared in his answers to other questions. The need to make this distinction is the reason for his rather elaborate description involving tangents and initial directions. This student did not have a need to describe field lines simply in terms of lines in iron filings, or trajectories followed by particles in a field, but could make the more abstract statement above.

That statement also contained the idea of local field direction at a given point, integrated with the student's picture of field lines. This ability was lacking in the responses from Conrad, and from most of the class, as seen in chapter 5. By contrast, Forrest was able to work with the idea of vector field strength at a point, both in the above, and in more quantitative questions. Even though he was able to use this vector idea of field strength, he was still not able to relate it to potential in fields. In fact, none of the class surveyed were able to describe this relationship.

Unlike the majority of the class, including Conrad, the difference between electric and magnetic fields was clear and consistent in all of Forrest's responses. He explained the distinction in quite abstract terms, as seen below.

> *Interviewer: You talked about magnetic and electric fields. Would you like to explain the difference between them, if any?*
> *Student: ... An electric field describes theoretical notions of electrical point charges ... magnetic field would be the same thing for a magnetic point charge, what's the word I'm looking for - a magnetic monopole. But there's no such thing, at least, none has been observed.*

The above response reached a level of abstraction beyond that directly requested by the question. The mention of monopoles is an example of the student working to make connections with other knowledge to form a consistent abstract system in his mind. His above response, abstract in nature, was validated in the light of his responses to a range of concrete questions involving the distinction between magnetic and electric fields.

While abstract, formal mode, responses predominated in Forrest's work, there were exceptions. It was reported in chapter 6 that none of the students surveyed had an abstract understanding of flux in fields, and this included Forrest. However, it is of interest to examine his responses regarding flux, as they showed a tendency to search after abstract meaning, and an unwillingness to be satisfied with less. While he was able to do a calculation involving flux, he still said, "I've yet to understand a definition of flux". He was dissatisfied with his description of flux as "field lines per unit area", and wondered whether flux was a vector or a scalar quantity. He was attempting to produce an abstract response, but simply did not have enough information to do so. This tendency to abstraction could also be seen in his understandings of phenomena related to fields.

Forrest's understanding of related phenomena

This student's grasp of abstractions related to field representation followed through into his predictions about the nature of phenomena related to fields. Trajectories of single particles in fields were handled through the abstract concepts of field lines and field vectors, as well as the relationship between potential and kinetic energy. Description of moving charge within fields used consideration of the charges in the circuit, in order to predict the macroscopic observables such as current. This was in contrast to Conrad, who reasoned from current to predict particle movement, and was hence unable to consider the effects of the constraints on particle movement due to the fields of the particles themselves.

Single charges moving within fields were handled skilfully by Forrest, who reasoned in terms of the mechanics of the forces on these charges. A clear distinction between electric and magnetic fields made accurate predictions possible where this distinction was relevant. As shown by the initial quote above, this student was clearly aware of the difference between field lines and the paths of particles in a field.

He did appreciate the feedback between moving charge in a conductor and the electric fields in that conductor, as seen in this quote, which refers to a situation where a wire has been placed in an electric field between points A and B:

> *Student: [reads] "Would a current flow?" Yes, but only for as long as it took for the electrons to get to B and set up an electric field within the conductor which will oppose the motion of the electrons because of course you're not going to get any net current, no flow, simply because you haven't completed the circuit ... You will get a very small initial current if you place a conductor in that field because the electrons will move over slightly towards the positive charge but because of the increased concentration of electrons at one end of the wire you're going to get an opposing electric field so the electric field in the conductor will be a net zero and of course once it reaches zero, you're not going to have any motion of electrons at all.*

In the above, he used the idea of charged particles in the circuit as a tool for prediction of current phenomena. This contrasts to the response of Conrad to the same question, as discussed above. Conrad was only able to make a prediction about current based on the idea that there should be a potential difference, then made a prediction about particle movement based on that idea; he did not use the model of charged particles to make predictions about current. Forrest was generally able to see the connection between currents and fields on the one hand and charged particles on the other. The notion of "field in the conductor will be a net zero" in his response above implies a level of sophistication in vector representation of fields. This level of overview of the system was unusual among the students surveyed, and is characteristic of the formal mode of the SOLO Taxonomy. He also saw this connection in the context of forces and induced currents caused by motion in a magnetic field:

> *Interviewer: You've already said how you'd predict the direction of a force on a charge moving in a magnetic field. And how did you predict the direction of a current caused by moving a wire in a magnetic field?*

Student: It's exactly the same, because a current is just moving charges, so the direction of force on the charges is [pause] is going to be the direction that the charge is moving, and that's all that a current is ...
Interviewer: O.K., and what about the force on a wire carrying a current through a magnetic field?
Student: It's exactly the same thing again in fact, coz you have moving charges, this time you're not treating the direction of their motion as the direction of the force, this time you're treating the direction of their motion as the initial velocity.

In the above, there is another example of predictions about current being based in this student's ideas about the charged particles in the circuit, which he used as a means of exlaining phenomena. Forrest was able to make accurate predictions about phenomena related to fields, based on an overview of the system involved.

Overall comments on Forrest

Forrest showed a level of insight into the system of electric and magnetic fields which was exceptional among the students surveyed. His abstract representations of fields were of use in making predictions about phenomena related to fields. Understanding of the field vector, and its complicated relationship to field lines, led to an understanding of potential. These abstract concepts were used in his predictions about movement of charge in fields, and allowed him to perceive the feedbacks and relationships involved. His responses show that an abstract understanding of field representation does allow for a full explanation of related phenomena.

Characterising Forrest's answers was the attempt to fit all information into an abstract system based on principles. He was able to use concepts as tools to solve problems. These concepts included the field vector; potential and energy; and the idea of moving charged particles in conductors. His understanding of these concepts was sufficient for him to consider the implications of a situation in terms of them, and to consider the situation in terms of the constraints imposed by these concepts. The concepts have an abstract nature, and cannot be fully understood on the basis of simple pictures.

Even where he was not able to come to a full explanation of a topic, such as flux in a field, he endeavoured to relate it to an abstract system. This consistent use of abstraction was in contrast to Conrad, and the majority of students in the class.

CONCLUSION AND IMPLICATIONS

These two students showed examples of responses characteristic of the concrete symbolic and formal modes of the SOLO Taxonomy, respectively. It must be emphasised that this does not imply that either of the students can be labelled as a concrete symbolic or a formal individual, not even in the relatively narrow context of their understandings of fields and related phenomena. In fact, their ways of thinking about the subject each contained elements of a number of modes of the SOLO Taxonomy. These two students were selected because their tests and interviews each contained a large proportion of responses characteristic of the concrete symbolic and formal modes, respectively.

The largely concrete symbolic picture of fields held by Conrad has a number of implications for those designing learning experiences in this area. Conrad is a university student of physics who also completed physics in high school. His levels of understanding were typical of the first-year physics students surveyed. Any difficulties he has with the material are likely to be common to many physics students, particularly at school level. Conrad's difficulties and tendency to concrete ideas are a useful guide for educators.

His difficulties with use of equations involved a failure to use principles to guide the use of these equations. While he could perform routine substitutions and use routine algorithms, non-routine calculations and proofs were not well addressed. To a large extent, this resulted from an inability to come to terms with the abstract forms of field representation which were the basis of these equations.

Conrad had difficulty relating to abstract concepts of field lines, and tended to see them as concrete entities, particularly as paths followed by particles in the field. This was a very common picture among the first-year university students surveyed. It seems that it may be best, particularly at lower levels of study, simply to accept this picture when first teaching students about field lines. It is easy to grasp, and could perhaps be seen by physics educators as a good first approximation to the field line concept as used by scientists.

The concrete symbolic system of reasoning used by Conrad also did not clearly involve particles in reasoning about phenomena. While particles were used in descriptions, they seemed to be mentioned only after the student had decided what was likely to happen. It is *possible* to integrate particle-based reasoning into understanding of field-related electrical phenomena, as seen in Forrest's responses; however, Conrad was far more typical of the class studied. Conrad's responses demonstrated that a particle-based model is not predictively useful unless the student also has an ability to work with abstract representations of fields. In light of the difficulty which it can cause until a formal-mode overview of the topic is reached, perhaps it is not wise to expose students to particle-based reasoning in their introduction to electricity.

Where Conrad's concrete symbolic responses were typical of the class surveyed, Forrest's formal responses were exceptional. Forrest's responses were characterised by an ability to phrase concepts in abstract terms. His ideas of field lines, for example, were independent of the need for a concrete referent such as trajectories, and were explained in terms of an abstract definition. He was able to fit field lines into an overall system of explanations involving all the concepts covered.

Similarly, Forrest was able to explain phenomena in terms of charged particles where this was appropriate, fitting charged particles in to a general network of relationships between electro-magnetic phenomena. Where Conrad was not capable of using a model of charged particles as a predictive tool, Forrest was. Forrest used the ideas which constrain the movement of these charged particles, and could see the effects which the movement of these particles has on the fields causing them to move. There appeared to be a significant need for an ability to work with abstraction in order to use these concepts. Conrad, with his concrete symbolic view, is most useful as a guide to planning of instruction in this area; Forrest is interesting as an example of formal mode responses about the area.

Comparison of the two students described in this chapter has served to highlight the difference between the concrete symbolic and formal modes of the SOLO Taxonomy. It has been possible to consider some common misconceptions about the subject in context of Conrad's overall knowledge of the area. These misconceptions have implications for teaching of the subject, as do the outcomes about the students' general cognitive structures, and the interaction between representations of fields and consequent understandings of field-related phenomena. Having integrated the results of the preceding chapters in the context of these case studies, the next chapter concludes this thesis.

Chapter 8

CONCLUSION

This thesis has characterised students' understanding of electric and magnetic fields, through analysis of written tests and interviews. Students' understandings of fields, as well as being interesting in themselves, have implications for the teaching of electric circuit phenomena, which is a recurring theme in the literature.

The first section of this chapter summarises the findings of this study, looking first at students' use of equations in this topic area, then examining their qualitative understandings of field representation, and of related phenomena. The case studies which were used to unify the findings are also discussed in this section. Leading out of the findings, the second section of this chapter relates this work to previously published literature about electricity and magnetism. The third section relates the findings to existing theoretical frameworks used in science education, and considers the implications of the findings for the SOLO Taxonomy in particular. The fourth section, in light of the findings and the related literature, suggests a number of possibilities for further research in this area. This is followed by a section which considers the implications of the current study for improvement of teaching and learning of this topic. The chapter concludes with an overall discussion of the findings and implications of the current work.

SUMMARY OF FINDINGS

There was a strong tendency for these first-year university students' concepts of electric and magnetic fields and related phenomena to be dominated by concrete pictures. Students, in general, were unable to connect these concepts with the quantitative material being taught in the course. It seemed that they were not able to organise the material into a consistent framework.

Students' difficulties with the quantitative material in the coursework were seen in chapter 4, where their responses to the course's assessment tests were analysed. Students did not appear to use principles to guide their use of equations in these questions. This was seen in use of inappropriate equations in problems, and was also seen in students' inability to produce mathematical proofs when requested. By contrast to this emphasis on equations in the assessment tests, the test and interviews conducted especially for this survey used qualitative questions to collect data on students' understandings.

Analysis of this data on qualitatative understandings was carried out under two broad headings: field representation, and related phenomena. Students ideas about field representation naturally affected their understanding of related phenomena, including electric circuits. This section is divided into sub-sections devoted to use of equations, understandings of field representation, understandings of related phenomena and case studies of individual understandings, respectively.

Students' use of equations

Chapter 4, was focussed on students' use of equations, as shown by their responses to the course assessment tests. The overall impression which emerged from this chapter was that the majority of students were unable to use principles to guide their use of equations. There was a strong tendency for students' responses to be dominated by equations which had been remembered, but were not tied together in students' minds.

A variety of strategies was seen in students' responses, but few of these used principles. While some students provided equations unrelated to one another, others were able to present algorithms, and a rare few were able to manipulate the equations, based on an understanding of the system of equations. Students' responses were poor even within the criteria set by the teaching department, with average scores below 50% for both assessment tests.

It was common for students to provide equations which did not relate to the situation of the question. An example of this, which recurred through various questions of the assessment tests, was students' confusion between equations relating to constant electric fields as opposed to radial electric fields. Few showed ability to use concepts such as energy in answering questions. This inability to use concepts was also visible in difficulties with proving results. Few students appeared to have the sophistication to prove results, with most simply assuming the results which were to be proved. It seemed that these students may have had difficulty with the very concept of proof.

While students' responses to these tests showed a general inability to use the concepts which underlie the equations used, their responses did not cast a great deal of light on the nature of students' own conceptions about the topic. This was due to the closed and routine nature of the questions in the assessment test. The nature of students' own conceptions was the focus of later chapters.

Students' understandings of field representation

Chapter 5 examined students' understandings of field representation. In that chapter, it became clear that there was a wide gap between abstract understandings of fields, which were used in the teaching materials, and the more concrete understandings that the students displayed. The abstractions presented in the teaching materials centred around the use of the field vector, whereas the ideas of the students generally centred around field lines, which were seen as representing directly observable phenomena, such as, particle trajectories. The SOLO Taxonomy was used to describe this gap between abstraction and concreteness, as is discussed later in this chapter. The current sub-section examines first the students' use of field lines, then their use of the field vector.

Field lines were a key organising concept for students. Even the least able could talk about field lines in some sense. For the majority of students, field lines were used to explain a wide range of phenomena. These included the paths of charged particles in fields, the interaction between fields and the formation of patterns in iron filings near a magnet. In all these cases, students saw the field lines as corresponding to something which was directly observable.

An analogy for the difference between a concrete and an abstract understanding of field lines was given in chapter 5, where figure 5.5 presented a road map and a weather map side by side. The lines on the road map represent concrete observables - roads, rivers, towns and so on. The isobars on the weather map are the result of an abstract definition, and do not correspond to any direct observables, only being useful when their definitions are understood. While field lines are in reality as abstract as the isobars of a weather map, most students saw them representing something as directly observable as the lines on a road map.

For example, most students saw field lines as corresponding exactly to the paths which would be taken by charged particles in the field. There are arguments for and against confronting this particular belief, which are examined in the section of this chapter on implications for teaching and learning. Their concrete way of conceiving field lines was used by students as an alternative to more abstract ideas involving the field vector. A view based on field lines was not entirely satisfactory, due to its incompatibility with the quantitative treatment of fields by equations. As the physics course had a strong emphasis on the use of equations, the students had no intuitive framework into which to fit their course material. The result was a lack of a qualitative grasp of situations, even when students were capable of manipulating the equations.

In order for students to interpret the course material into a consistent framework, they had to be able to reason using the field vector. This idea of the field vector is central to the mathematical formalisms about fields, and was missing or poorly developed in almost all of these students. Their exposure to the course material meant that students were generally able to use the field vector in equations, when it was supplied to them. However, they were unable to form a clear picture of its meaning in qualitative situations, such as a charge moving between two magnets, or the combination of two fields. There was a failure to use the idea of the field vector as a tool in their reasoning. They were also unable to relate the field vector to the field lines, which they used to explain such situations. Field lines can be used in a conceptually simple fashion, understanding them as paths that particles take, or reasoning in terms of repulsion between lines. The field vector, and the concept of a vector associated with each point in space, requires a more abstract form of reasoning. This split between simplicity and abstraction relates to a major shift in student thinking.

In keeping with the students' widespread inability to use abstract ideas to represent fields, the concept of flux was not fully available to any of the students. When asked to describe and use flux, many were able to make statements involving field strength and even area. However, none of them were able to explain or use the relationship between field strength, area and direction which defines flux. It appears that they were unable to make this link, which involves consideration of the field vector, and has an abstract nature.

Students' representations of electric and magnetic fields were generally based on directly observable quantities, rather than an ability to use abstractly defined ideas. Their concepts were often based on field lines. The more abstract concept of the field vector was not integrated into students' ideas about fields, and they were not able to use it as a tool in their reasoning. As the coursework was based on equations involving the field vector, the students had no intuitive framework which would allow them to incorporate the course material. This meant that they often lacked understanding of concepts, even where they could undertake questions based on application of known formulae related to these concepts. Students' poor understandings of field representation had repercussions for their understandings of related issues.

Students' understandings of phenomena related to fields

Students' representations of fields determine their ability to explain phenomena related to fields. In chapter 6, this thesis reported the investigation of students' understanding of potential, current and charged particles in conductors, in relation to electric and magnetic fields. The current sub-section examines students' understandings of these three concepts in turn.

Students' understandings of potential and voltage in the context of fields were poorly developed. As part of this, they generally identified potential with field strength, rather than using the energy definition of potential. This relates to their focus on the concepts of field strength and field lines in their representation of fields. Of course, in physics, potential actually relates to field strength exactly as energy relates to force. Energy itself is known in the literature (Driver & Millar, 1985) to be a problematic concept for students, and understanding of energy is an essential pre-requisite for understanding potential. The fact that students have such difficulties with potential in fields has implications for their learning about circuits. It indicates that teaching about voltage in circuits, through potential in electric fields, requires attention to students' concept development. The concept of potential, tied as it is to the concept of work/energy, would seem to require careful introduction to be meaningful to students.

At the same time as students had difficulty with potential and voltage, the idea of current presented problems for them in field-related contexts. While they could talk about a current flowing, they had varying levels of understanding as to the meaning of this. Many confused current with field, in the context of a capacitor. There was general confusion as to the nature and effects of current. Students relied on simple rules to predict the existence of a current. These rules often included the existence of a "potential difference", but students' lack of grasp of the idea of potential made it impossible to produce complete predictions with these rules. In particular, they rarely saw the changes in field strength and potential which resulted from movement of charged particles in electric currents.

The idea that charged particles were moving in conductors was familiar to students. However, they generally applied this idea only after they had decided what would happen, without using this model. For example, they decided that a situation with a bar moving in a magnetic field should result in an induced current, based on simple ideas that movement in a magnetic field produces current. They rarely used particle models in this prediction. When asked specifically about particles in that situation, they said that current was moving particles. However, they were not generally able to explain why this situation should produce a current in terms of the effect on charged particles in the conductor. The conditions and constraints on movement of these charges were not apparent to them. They could not see the effects which charge movement would have on the fields causing that movement.

The widespread failure of students to use the charged particle model effectively in their explanations raises questions about whether it is appropriate to emphasise this model in teaching. These questions are explored in the section of this chapter on implications for teaching and learning. It seems that this reasoning in terms of charged particles had an abstract nature which was beyond most of the students. The notion of abstraction in responses was further explored in the in-depth studies of individual students.

Studies of individual students

The in-depth studies of individuals in chapter 7 had two main themes: integration of students' understandings across the range of questions in the instruments, and comparison of the understandings of these students. Consideration of the two individuals' responses across the range of questions showed a balance between consistency in application of key ideas in some questions and *ad hoc* use of weakly related concepts in other contexts. Comparison of the students served to highlight the contrast between the nature of their understandings.

The individual studies gave a source of data regarding the link between field representation and related phenomena which has been discussed above. In the context of an individual, it was easier to perceive the relationships between concepts which had been addressed in separate questions. For example, it allows an individual's responses to various questions concerning field lines to be compared, with an explicit focus on the degree of consistency with which that student responded. As a result of this comparison, it became apparent that the average student chosen for the case study (referred to as Conrad in chapter 7) tended to produce answers that were non-systematic and context dependent. The only unifying concepts that he used seemed to be those of field lines and attraction/repulsion. This student's use of other, more abstract, concepts was generally handled on an unsystematic basis, without evidence of underlying principles guiding his understanding.

Comparison between the students showed that they each had a consistent style of learning about this topic. The student referred to as Conrad was generally linked to understanding all concepts in terms of concrete referents in the real world; any more abstract concepts tended to be misapprehended on this basis, or repeated without evidence of connection to the rest of the student's knowledge structure. In contrast to this, the student referred to as Forrest had a style of learning which consistently attempted to explain data within an abstract structure. He was able to use abstract concepts such as the field vector and movement of charged particles as tools in his reasoning, in order to unify phenomena which had different surface details. There was an ability to use concepts to come to novel explanations and procedures, rather than an emphasis on recall of facts and algorithms. This approach generally placed Forrest's responses in the formal mode of the SOLO Taxonomy, where the responses of the other student were predominantly in the concrete symbolic mode.

By and large, the students in the study resembled Conrad far more than Forrest. The abstract concepts which were taught were not grasped in any systematic way by the majority of students, with concrete concepts as the only unifying parts of their knowledge structures. In particular, a simplistic notion of field lines was a unifying feature for most students.

RELATION OF CONCLUSIONS TO THE LITERATURE

This section starts from the fact that most of the work on understandings of electric phenomena in the literature is concerned with circuit electricity. It reasons from there by examining suggestions that circuit electricity can usefully be taught through teaching about electric fields. These suggestions imply that students' understandings of electric fields are of importance for teaching them about electric circuits. Then, the recurring themes of students' understanding of concepts in circuit electricity (voltage, current, electricity) are examined in light of the data from the current study, to see whether the observed misconceptions about these concepts are also present in students' understanding of electric and magnetic fields. After this, previous findings about students' understanding of electric and magnetic fields are compared with and expanded by the observations of the present study. Ideas about electric current and electromagnetic fields are both relevant to understanding of electromagnetically induced current, a topic for which students' understandings have not previously been described in the literature.

The majority of investigation into understandings of electricity and related concepts has been concerned with circuit electricity, with some work on students' understandings of electric and magnetic fields. It is common in physics texts (e.g., Arya (1979); Giancoli (1989); Ostdiek & Bord (1991); Smith & Cooper (1964); Sears, Zemansky & Young (1992); Wilkinson (1989); Young (1992)) to start with electrostatics and move to electrodynamics, that is, from electric fields to electric circuits. This parallels the historical development of the subject. Stocklmayer, Treagust and Zadnick (1994) suggested more recently that circuit electricity could usefully be approached through field concepts to emphasise the holistic aspects of an electric circuit. The insight this thesis gives into students' understanding of fields, both in themselves and in the context of electric circuits, is of particular interest in the light of teaching schemes that approach circuits through electric fields.

In the literature, students have repeatedly been found to hold misconceptions about circuit electricity. Reports (e.g., Cohen, Eylon & Ganiel, 1983; Millar & Beh, 1993; Millar & King, 1993) that students had trouble with the concept of voltage in circuits led to the investigation of student understandings of voltage and potential in electric fields as part of this thesis. The finding here was that student concepts of potential were also poorly developed in connection to fields. Even the most able students did not fully grasp the relationship between electric potential and electric field strength, and few could relate electric potential to energy. The finding that students often view current, voltage, "electricity", charge and electrical energy as interchangable when reasoning about electric circuits (Arnold and Millar (1987); Shipstone (1985)) was carried into the domain of electric fields by this thesis. The subjects of this thesis were observed to confuse electric fields with this same interchangable idea of "electricity". Those thinking in this way saw field lines in terms of flow of this same "electricity". They predicted, for example, that the electric field lines in a capacitor would disappear when a resistor was carrying current between the plates of a capacitor. They saw both the current and the field lines as being "electricity", with no clear distinction between current and field.

Confusion between current and field was also reported by Andersson (1984), who observed that students explained an electromagnet by postulating a current running out of the wires to make it work. The magnetic fields of current were found to be problematic by Psillos, Koumaras and Valassiades (1987), who called for further investigation into the topic. This thesis investigated the effects of student misconceptions about current on their predictions for the magnetic fields of current. It was found that misconceptions about current did carry on into predictions about the magnetic field, which implies that students were in fact connecting the two issues in their minds, rather than applying given facts about the magnetic fields. The link between currents and electric fields was the theme for Eylon and Ganiel's (1990) paper and to a lesser extent Steinberg et al's (1993) Capacitor Aided System for Teaching and Learning about Electricity (CASTLE) project. Eylon and Ganiel, working from the perspective of electric circuits, found that there was a "missing link" between electric circuits and electric fields in students' reasoning. This thesis, working from the perspective of electric fields, found the same result for students' reasoning about transient currents. This suggests that any attempt to teach about circuits starting from fields must allow students some opportunity to form that missing link.

Teaching about circuits through fields was suggested by Stocklmayer, Treagust and Zadnick (1994). The findings of this thesis about the details of students' understandings of fields have relevance to such a scheme, particularly, the findings about understandings of circuits as they relate to electric and magnetic fields. These findings draw on, and integrate a number of, previous papers specifically discussing aspects of students' understanding of fields, as discussed below.

Among this previous work was the finding by Viennot and Rainson (1992) that university physics students tended to have difficulty using the electric field vector in field interactions. The current study has taken the theme of the field vector, and examined it in a wider range of situations, integrating it into the findings of Maloney (1985) regarding students' confusion between electric and magnetic fields. This thesis has found that students only used the field vector with magnetic fields when they had some cue to do so, such as being given the vector as part of the question. Their failure to use the field vector was linked with their failure to distinguish magnetic from electric fields. This was probably because their learning about magnetic fields had used the magnetic field vector, without making links between this vector and their grasp of other situations. Students' understandings of the field vector were further defined by this thesis. While the subjects of this thesis were aware of vectors as having magnitude and direction, and were able to draw arrows which they described as vectors, it was not common for students to appreciate the idea of a vector associated with each point in a field, and to be able to express clearly exactly what the direction of the vector meant. This made it impossible for them to apply vector superposition in cases of field interaction, such as, that described by Viennot and Rainson (1992). Their approach in these cases was based more on field lines.

As Törnkvist, Petterson and Tranströmer (1993) pointed out, students' understanding about movement of charged particles in electric fields tends to rely too heavily on field lines. Galili (1995) suggested that this was linked to students' use of intuitive Aristotlean mechanics. The current work examined this issue as it related to the field vector in situations involving both movement of charged particles as in Galili's (1995) work and interaction of fields as in Viennot and Rainson's (1992) work. The finding, given in this thesis, was that field lines tended to dominate students' qualitative thinking about electric and magnetic fields, although they did try to use the field vector in some situations involving equations. Poor qualitative grasp of problems for which students could perform calculations was seen here. This is consistent with findings reported by McMillian and Swadener (1991) and Fergusson-Hessler and de Jong (1984) in the specific area of electric fields, not to mention the general thrust of a large body of constructivist literature in physics education. As well as expanding findings from previous authors' work, the current thesis did explore students' understandings of a topic not previously researched.

This thesis dealt with an area of phenomena not previously covered in the literature, that of induced electric current. Questions concerning this tied together the issues mentioned above, namely: differentiation between electric and magnetic fields; the use of the field vector and direction; use of field lines; the relationship between macroscopic currents and microscopic particles; and the effects of current. Induced electric currents involve both electric and magnetic fields. It was found that students' differentiation between electric and magnetic fields was based on prompts from the situation rather than any deep conceptual understanding. If they were shown a diagram with a bar or wire moving across a field, then they tended to apply the rules about sideways movement across a magnetic field. If identical situations were shown for particles moving in electric and magnetic fields, respectively, the lack of extra cues made it impossible for the students to distinguish between the two. Where the cues indicated use of the field vector, then it was used, in some form. When students were considering induced currents and movement of wire through magnetic fields, they did not generally use field lines as part of their system of reasoning. The concrete view of field lines suggested by Törnkvist, Petterson and Tranströmer (1993) was not a feature of their reasoning about the topic of induced currents. The reasoning observed in the current thesis was heavily linked to particular situations in a way which implied that it was likely to be based on isolated packages of knowledge, many of which may have been rote-learned. They were unable to form the sort of links between particle models and bulk currents and voltages which were discussed by Psillos, Koumaras and Valassiades (1987).

Consideration of the literature was a feature which guided the development of this thesis, and a number of issues from the literature have been clarified by the current study. Suggestion in the literature that electric circuits could be taught in terms of electric fields led to an investigation of students' links between these two ideas. Discussion of voltage in the literature led to a finding here that voltage and potential were also poorly understood in the context of electric fields. Papers on field lines, field vectors and representation of fields led to an interest in the way these relate to one another in a variety of situations. Among these situations was induction of electric current, which ties together a number of themes and has not previously been the subject of an investigation of students' understandings.

IMPLICATIONS FOR THEORETICAL FRAMEWORKS

Chapter 2 discussed theoretical frameworks currently prevailing in science education, and the place of this study within those frameworks. That chapter made a number of statements based in the literature, which are summarised in the current paragraph. Within the field of science education, the dominant theoretical paradigm is a broad constructivism of the type which von Glasersfeld (1995) referred to when he described Piaget as a constructivist. This point of view places heavy emphasis on the knowledge structures of the students' understanding. The current thesis has made an investigation of students' understandings of fields and related phenomena, from a broadly constructivist outlook. Within a constructivist way of working, there is a need for a method of assessing students' understanding, particularly a method that can be applied by teachers in classrooms; the SOLO Taxonomy appears to have the potential to fill that need. This thesis used the Taxonomy as a means of assessing students' understandings. The Taxonomy is particularly interesting in this context, in that it allows a generalised comparison of knowledge structure across topic areas, which complements study of students' understandings of specific topics. Development of the Taxonomy is intended to provide an assessment technique that allows everyday investigation of students' knowledge structures.

As well as being a possible classroom-based system, the Taxonomy offers a theoretical framework for the investigation of students' conceptions. It comes out of cognitive psychology, and is compatible with a broadly constructivist viewpoint. The methodology of investigation using the Taxonomy includes a phenomenographic analysis of data, as has been used elsewhere in the literature (e.g., Dahlgren & Marton (1978); Marton (1986); Linder (1993); Walsh, Dall'Alba, Bowden, Martin, Marton, Masters, Ramsden & Stephanou (1993)). In addition to backing from the literature, the Taxonomy has a persuasive internal consistency. The logic of the Taxonomy, based on consideration of elements of information in students' minds and the connection between them, offers great generalisability across topic areas. At the same time, the way it breaks up all learning into units of knowledge and connection between them has a certain logical inescapability - it is difficult to think of any topic area where one could not apply this organisation. The combination of support from the literature and internal logic led to the choice of the SOLO Taxonomy as the theoretical framework for this thesis.

In the course of the thesis, the use of the Taxonomy did allow for useful statements about students' knowledge. Analysis of the logical elements of students' thought allowed these elements to be compared across the range of test questions which the students answered. Consideration of the connection between these elements of thought in students' minds allowed for a consistent description of the difference between students, and had implications for future instruction in the subject. The Taxonomy provided a framework in which analyses of all the test questions were drawn together, to allow an overall statement about students' responses across the entire range of test questions and topics. The overall conclusion reached through use of the Taxonomy was in terms of levels of connection and abstraction in students' work.

While exploring students' responses using the Taxonomy, it was possible to further develop the Taxonomy itself, as the responses were of a level of abstraction which had not previously been investigated in science by using the Taxonomy. This has allowed for a deeper insight into the nature of the formal mode of the SOLO Taxonomy. In brief, responses in the formal mode display a qualitatively higher level of abstraction than those in the concrete symbolic mode. Few studies using the Taxonomy have previously reported on responses in the formal mode, and it was of interest for this thesis to characterise responses in this mode.

The students in this study responded in the concrete symbolic mode and formal modes of the Taxonomy. Their formal mode understandings would generally have been classed as transitional to the formal mode in terms of the 1982 (Biggs & Collis) interpretation of the SOLO Taxonomy. The recent development of multiple learning cycles within the modes of the Taxonomy was discussed in chapter 2. The cycles identified in this work are the last cycle of learning in the concrete symbolic mode and the first cycle in the formal mode. This corresponds to the levels of understanding observed by Pegg and Coady (1993) in students' responses to algebra questions. The formal mode responses are only beginning to develop a complete overview of the situation. This complete overview was the definining criterion for a unistructural response in the formal mode according to the 1982 (Biggs & Collis) version of the Taxonomy. As a result, the formal cycle of learning identified here is fine structure which does not equate to the formal learning cycle in the earlier version of the Taxonomy. However, the students' responses in this cycle do have the essential abstract quality which defines the formal mode.

As a result of the incomplete overview in their abstract, formal mode, understandings, students often had to fall back on the concrete symbolic mode to provide overall structure to their answers, because their formal mode understandings were generally insufficient to give full explanations of phenomena. Formal mode understandings were characterised by attempts to explain events by using abstract concepts which were not directly linked to concrete referents. For example, students generally focussed on field lines as an organising feature, and saw these in terms of directly observable phenomena, such as, particle trajectories in the field. They were generally unable to describe situations in terms of the field vector, which is not a directly observable quantity. While most students could describe the field vector itself to some extent, they were unable to use it as a concept in explaining given situations. The level of abstraction in the concept of the field vector placed its use in the formal mode of the Taxonomy.

While application of the field vector was in the formal mode, description of it was common in students' responses. This highlights the point that description of concepts can be performed in the concrete symbolic mode, in terms of simple rules, but that use of these concepts, particularly without prompting, involves a higher level of response. This point also applied strongly to the idea of charged particles moving in electric circuit situations. While students were able to say that "a current is a flow of charged particles", they did not display an ability to use this idea of charged particles in their reasoning. They were incapable of using the conditions and constraints on charge movement which result from the charged particle model. In particular, they were unable to see the effect of the fields of the moving charged particles. This led to unrealistic predictions, and was the result of the inability to use the abstractions involved in this charged particle model, which were of a formal mode nature.

The separation between concrete symbolic and formal modes was in terms of use of concrete referents. Responses in the formal mode of the SOLO Taxonomy were able to go beyond direct observables, to use pictures and models which had elements of abstract definition. The models were used as tools in these students' reasoning, and the students were able to deal with the conditions and constraints inherent in the models. By contrast, responses in the concrete symbolic mode were tied to the real world, in that all concepts had to have some direct referent. This has helped to further clarify the difference between the concrete symbolic and formal modes of the SOLO Taxonomy.

Further questions arising from theoretical frameworks

A number of further questions arise out of the theoretical framework of this thesis, and are discussed here. It was found that most of the students in this study responded at a low level, in terms of the SOLO Taxonomy. This invites the question of whether this low level is inherent in the students, or whether it could be influenced by teaching. Use of the Taxonomy to investigate students' understandings in this study raises the question of how the SOLO Taxonomy could best be applied to investigate students' understandings in an assessment system.

The difference between the concrete symbolic and formal modes of the Taxonomy was seen in the styles of individual students. Whilst many students had a mix of responses from each mode, the organisation of most responses was based on the concrete symbolic mode. A question naturally arises from this: Are these students capable of learning in the formal mode, or does the instructional course assume too high a level from them? The question is beyond the scope of this study, which has concerned itself with the Structure of the *Observed* Learning Outcome for these students. One can postulate that university students would normally be capable of reasoning in the formal mode, and that a teaching course which was based on their existing knowledge may be able to bring them to respond in this mode. Such a course could start from their existing concrete symbolic levels of understanding and lead them through levels to the formal mode, as opposed to simply providing them initially with formal mode abstractions. Further research involving a teaching course would address this question of whether student performance can be improved in terms of SOLO levels of response. The SOLO Taxonomy does not classify the maximum achievable levels for individual students, but merely the levels which they have already displayed.

This thesis used a phenomenographic technique of analysis to find groups in students' answers, with these groups then being described in terms of the Taxonomy. This method is commonly used by research studies of students' conceptions using the Taxonomy as a framework. The phenomenographic method of finding groups is labour intensive, and therefore seems unlikely to be suited for classroom use. If a phenomenographic approach is required for valid use of the Taxonomy by university researchers, then it would seem that valid use of the Taxonomy in the classroom could only be achieved on the basis of some sort of criterion referencing. One might suggest that criteria could be set on the basis of SOLO research studies into every topic area covered in the syllabus, to allow lists of knowledge points and connections between them to be given for each area of study. However, this would involve a great deal of research effort, and the resulting lists of points could invite rote learning in classrooms. Alternatively, each science teacher might be shown the principles of the Taxonomy, and allowed to implement these principles by themselves. However, it seems far from certain that teachers would automatically agree as to the levels of reasoning involved in various learning outcomes. In this case, student assessments would not be consistent across teachers. This raises the question of whether teachers could be brought to consistent use of the Taxonomy, and what sort of training would be required.

Contemplating the implementation of the SOLO Taxonomy into the education system, one wonders how to cope with the dilemma confronting any system of assessment. On the one hand, the danger of excessive standardisation linked to lists of outcome points of knowledge, and on the other, the danger of a complete lack of standardisation based on individual teachers' interpretation of assessable points. It would be of interest to see studies of SOLO use in the science classroom, particularly from the point of view of consistency between teachers, and the level of training required to achieve consistency between teachers using the Taxonomy. SOLO could only be used for criterion-referenced assessment if it were possible to implement a high level of consistency of use across teachers and schools in an educational system.

FURTHER POSSIBILITIES FOR RESEARCH

This study has dealt in depth with a wide range of concepts relating to electric and magnetic fields, from a group of first-year students of university physics. A number of other possibilities arise. Related studies could usefully be undertaken on different groups of students, both at higher and lower levels of education. It would also be of interest to apply written tests to a large number of students, perhaps using the superitem technique of test design which comes out of the SOLO Taxonomy, as described in chapter 2. In terms of the SOLO Taxonomy, it would also be valuable to use this subject area to investigate the nature of multi-modal functioning. The study also raises some questions and suggestions about teaching and learning in this area. The current section explores the above possibilities.

The subjects of this study were first-year university students, but there are other interesting options. Investigation of younger students and their interactions with magnets and static electricity may reveal interesting ways of viewing these phenomena. Additionally, it would be informative to compare such views with the qualitative understandings of the university students, to see if there has been any significant development of qualitative understanding among the university students accompanying their increased knowledge of equations and algorithms.

While looking at younger students would help give a picture of the roots of the conceptions in the minds of first-year university physics students, an investigation of more advanced students could give a picture of which concepts are most important in further study, as well as showing which concepts are most resistant to change in the course of further study of the topic. A study of university physics students in later years, as well as graduates, research physicists and lecturers, would be useful on these grounds. It would also allow investigation of still higher levels of reasoning within the formal mode, which would be a new advance for the SOLO Taxonomy.

The large bulk of the in-depth interview data in this study has necessitated a relatively small number of subjects, and it would be interesting to carry out investigations on a larger sample, using a written test technique. Such a written test could involve the superitem technique of test generation, which comes out of the SOLO Taxonomy, and is discussed in chapter 2. In this method, each question is broken up into parts, each of which requires a higher level of understanding to complete. Writing superitem questions requires a good understanding of student levels on the part of the examiner; the investigation of student levels in this thesis forms a basis which makes possible the creation of subsequent superitem tests.

Within the SOLO Taxonomy, there is a recognition that students can bring more than one mode of functioning to bear on a problem or subject at the same time. Electric and magnetic fields would be an interesting area in which to investigate this multi-modal functioning. Study of this area involves a combination of diagram use, which has elements of the ikonic mode; calculation, which is generally in the concrete symbolic mode; and complicated models and reasoning in the formal mode. It would be useful in terms of theoretical frameworks to investigate the area with an emphasis on multimodal functioning, rather than the current study's emphasis on primary level of functioning in a response. This could lead to a greater understanding of the various modalities that have to be combined in teaching to help learners to a more complete understanding of the topic.

The current study was not focussed on teaching as such, being an investigation of students' understandings. Subsequent work could involve the design and testing of a teaching program about electric and magnetic fields and related phenomena. This teaching unit might be primarily concerned with teaching about fields, or might be concerned with teaching circuit electricity based on field concepts. It would take account of the findings of the present study, and attempt to avoid pitfalls in understanding which appear to be common in the light of this study. This would involve an attempt to start from students' existing concrete understandings of fields, rather than teaching abstractions which students had no way of relating to their existing understandings. It would also be interesting to include classroom use of the SOLO Taxonomy in such a teaching program. This would enable an assessment of the practicality of this Taxonomy in a science classroom. A pilot teaching program coming out of this thesis would be a useful piece of research. In the current study, learners have shown a tendency to reason in the concrete symbolic mode, as opposed to the formal mode which contains most of the target concepts for a university physics course. It would be desirable to design a teaching program which was based on a knowledge of this tendency in students, and specifically aimed to confront the concrete symbolic mode of reasoning.

IMPLICATIONS FOR TEACHING AND LEARNING

This study has found that students commonly fail to grasp the abstract concepts associated with electric and magnetic fields. Their thinking about the topic is organised by simpler, more concrete concepts, which has implications for teaching about electric circuits as well as about fields themselves.

The students had an intuitive picture of fields which was largely based on field lines. These field lines had a concrete character in their responses. Equations based on the field vector were not integrated into the responses. Rather, the equations were isolated fragments of knowledge for the students. The obvious implication of this for learning about fields is that teachers have to take care to link any equations with the existing concepts of the students; in this case, the students' conceptions are often based on visual concepts of field lines. If the material is not related back to this, then students have no way to structure it in their minds. A few students were able to form the links between field lines and the field vector in their course, but these students were the exception. It is not sufficient to ignore the students' original conceptions and teach the abstract material as if it were self-contained.

This raises the question of how to treat the students' original conceptions. Earlier in this chapter, the relationship between field lines and particle trajectories was flagged as a common area of misconception for students. The majority of them think of field lines as the paths that are followed by a charged particle released in that field. Should this misconception be confronted, and if so, at what stage? In favour of confronting this concept is the fact that it is not accurate, and leads to incorrect predictions for particle trajectories. This is particularly the case in magnetic fields, where charged particles do not even approximately follow the lines of the field. However, the idea that field lines are the paths followed by particles in the field is a simple concept, and easy to grasp. In the current study, the fact that this belief was held by the majority of students did not affect their predictions about movement of particles with initial velocity not parallel to the field lines. This indicates that the misconception is not damaging to all predictions about particle movement in the field. Due to the simplicity of this idea, it may be that it is preferable, in the initial stages of learning about this topic, to teach about field lines as "approximately" the paths followed by charged particles in the field. Attempts to do otherwise may be of an excessively abstract nature, and be beyond the comprehension of novice students of electric fields.

It is not uncommon to teach about electric circuits by starting with electric fields. The approach is often through "electrostatics", electric field phenomena, leading in to "electrodynamics", or circuit phenomena. Stocklmayer, Treagust and Zadnick (1994) suggested a version of this that emphasised the holistic nature of an electric circuit. The current thesis indicates that there are points that have to be considered in such an approach to electric circuits. Students do not easily come to an appreciation of the abstract concept of potential in the context of fields. Carrying this concept through to explain voltage in circuits is not automatically going to succeed. The students' learning about this topic has to be connected to their existing ideas in order for a meaningful idea of potential and voltage to result. Potential, voltage and current are complicated ideas, whether initially approached through fields or circuits.

The connection between electrostatics and electrodynamics is primarily in terms of the movement of charge within electric fields. In the current study, it was observed that students had difficulty reasoning in terms of the movement of charged particles. While they could apply simple rules for predicting currents, and then apply a rule that current is charged particles, they were seldom observed to make predictions based on the particle model. The students failed, in general, to account for the effects that followed from the movement of the particles. The notion of charged particles was not an effective tool in the reasoning displayed by the majority of students. It appears that understanding the effects of the movement of these particles requires a high degree of abstraction. In light of this, it may be appropriate to de-emphasise the role of charged particles in circuit phenomena. As an alternative, an emphasis on the role of fields in the circuit might help students to appreciate the effects of changes throughout the conductor.

Approaching electric circuits through consideration of electric fields is a workable procedure. However, this must be done in light of the knowledge that students have difficulty with concepts about electric fields, as well as difficulty in connecting knowledge about fields with knowledge about electric circuits.

OVERALL CONCLUSIONS

Generally speaking, the first-year physics students investigated were unable to connect their own understandings of fields to the more abstract material in their course. Their understandings consisted mostly of concrete concepts, and this made it impossible for them to fit the abstract mathematical approach of the course materials into their frameworks of knowledge. This difference can be described in terms of the gap between the concrete symbolic and the formal modes of the SOLO Taxonomy. These findings have implications for teaching and learning, both about electric fields and electric circuits.

The concrete thinking of the students was generally tied to direct observables; their thinking did not make use of concepts which were at a level of abstraction from reality. Such abstract concepts are the basis of a mathematical approach to this subject, which was the core of their university course. The result was that students were unable to relate their coursework to their existing understandings. In this topic area, the students' concrete ideas were centred around field lines. These were generally identified with concrete observables, such as, the paths which charged particles take in fields, or the lines which one sees in iron filings near a magnet. Students used these lines to reason about a range of phenomena, including particle movement and field interaction. This view centred on lines was not compatible with the emphasis of the coursework on this topic, which was about mathematical work centred on the field vector. Students were generally unable to relate the abstract idea of the field vector to their concrete ideas of field lines and intuitive situations. Student understandings were not generally internally consistent or complete, but such unifying structure as there was in their minds was often based on concrete field lines. There was no abstract unifying structure.

The SOLO Taxonomy offers a way to describe this gap between the thinking of the students and the abstract nature of the course. The concrete symbolic mode of the Taxonomy is used to classify responses where students reason in terms of symbols which represent observable things in the real world. This thesis characterised the formal mode in terms of students' ability to use concepts which have no direct referent in the observable world. The qualitative difference between the two modes is the reason students are unable to assimilate the course; their concrete symbolic reasoning is not a suitable framework for thinking about the formal-mode abstractions of the course.

Teaching in this area should connect with students' existing concepts. These concepts tend to be concrete and relatively low level, where the material in the university course was highly abstract. The difficulty of bridging between these two ways of thinking is considerable, and is the essence of what is required in this area, and physics teaching in general. In this specific topic area, teachers should be aware of the nature of the view students have of field lines, and the difficulty students have in connecting this to the abstract syllabus material involving mathematics and the field vector. Electric fields are sometimes used as an introduction to electric circuits, using field examples to develop concepts, particularly concerning potential and the movement of charge. It cannot be taken for granted that students grasp these abstract concepts within the realm of electric fields, far less that they are able to transfer them to a related area. Teachers must be aware of the difficulty students have in coming to terms with the abstraction implicit in study of this topic.

The difference between the concrete and the abstract is a recurring theme in human thought. In this thesis, a gap has become apparent between the abstract mathematical approach in the physics course on the one hand and the concrete ideas held by the students on the other. This has given insights into ways of teaching and learning about the subject area of electric and magnetic fields, as well as contributing to the development of the SOLO Taxonomy of learning outcomes. The findings are confronting, and highlight the difficulties faced by learners in this topic area, offering a challenge to future educators.

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