LIST OF APPENDICES

APPENDIX A

Previously published work (1994).

Guth, John & Pegg, John (1994). First-year tertiary students' understandings of iron filing patterns around a magnet. Research in Science Education **24** 137-146

This paper gave results which also appear in chapter 5 of this thesis, showing students' understandings about this phenomenon. The SOLO Taxonomy was used as the organising feature of the paper.

APPENDIX B

Previously published work (1995).

Guth, John. (1995). An in-depth study of two individual students' understanding of electric and magnetic fields. Research in Science Education **25**(4)

This paper gave results which also appear in chapter 7 of this thesis, concerned with gaining an overall picture of student understandings of electric and magnetic fields and related phenomena by in-depth study of two individuals.

An in-depth study of two individual students' understanding of electric and magnetic fields

This paper describes and compares individual students' understanding of a range of concepts associated with electric and magnetic fields. Data are drawn from written tests and detailed interviews of students from a first-year university physics class. The case study approach makes it possible to examine in depth the interaction between conceptions of various related topics in the students' minds. The theoretical framework of the SOLO (Structure of the Observed Learning Outcome) Taxonomy, as elaborated in a previous paper on this topic area by the author, is further advanced here. Using this framework, the paper provides insight into a more detailed view of students' understanding of fields, which in turn casts light on possible teaching strategies for fields and related topics.

Electric and magnetic fields are largely outside everyday experience; they are encountered in physics class, in more or less abstract form, where they are used to explain a range of related phenomena. While a large amount of work has been published on student understandings of circuit electricity, fewer papers have been published on understandings of fields. In this paper, an in-depth approach to individual students' concepts about a range of ideas associated with electric and magnetic fields is taken; this allows the link between the students' representations of fields and their consequent understanding of field-related phenomena to be made clear. Working from the theoretical framework of the SOLO Taxonomy (described at length later in this paper), the students are used to illustrate modes of functioning, which serves to develop this framework further. Hence, this paper contributes both to knowledge of students' understandings of fields and to the SOLO Taxonomy.

Electric and magnetic fields in the literature

Understandings of fields are of interest for a number of reasons: they are important in modern physics, they offer scope for complicated conceptions, and it has been suggested that introductory electric circuits could be taught by reference to field concepts, as detailed below. Few papers have dealt with students' understandings of electric and magnetic fields - Viennot and Rainson (1992) stated that, at that date, "the electric field itself, and more generally the notion of fields, has not been at the centre of any research on students' reasoning." In their own paper, Viennot and Rainson found that university physics students had trouble dealing with the idea of vector superposition in interacting fields. Törnkvist, Petterson and Tranströmer (1993) found similar conceptual problems in university physics students' understandings of field representations. A similar lack of qualititative grasp of the nature of interactions between electric fields was found by MacMillian and Swadener (1991), in a study of first-year university physics students. These papers all dealt with electric fields, without consideration of magnetic fields.

Guth and Pegg (1994) described university physics students' understandings of magnetic fields in the context of patterns in iron filings around a magnet. Their findings were consistent with the studies on electric fields above; students tended to confuse the representational concept of field lines with literal reality. Magnetic fields were treated much as electric ones.

Students' understandings of the relationship between electric fields and magnetic fields was the subject of two papers: Maloney (1985) reported that his university physics students commonly expected the effect of magnetic fields on charged particles to be identical to that of electric fields. Herrmann (1991), without reference to Maloney's paper, suggested that it would be desirable to teach about static magnetic fields by analogy to static electric fields.

Conceptual structures underlying the whole edifice of electric and magnetic fields and related phenomena were investigated by Fergusson-Hessler and de Jong (1987). They came to the conclusion that none of the students in their first-year university physics class had an understanding of electricity and magnetism which corresponded with a heirarchical knowledge structure for the area which had been constructed by those researchers. While that paper numerically compared the students' responses with an "ideal" knowledge structure generated by experts, there was little data given about the nature of the students' own knowledge structures in the subject. That is to say, no paper exists which describes students' knowledge structures across the complete area of electric fields, magnetic fields and related phenomena.

Electric fields are also of interest in the teaching of electric circuits. Stocklmayer and Treagust (1994) and Stocklmayer, Treagust and Zadnik (1994) suggested that an approach to electric circuits based on fields could avoid misconceptions related to the use of particle-based and fluid-based models of circuit behaviour. For such an approach, it is important to be aware of common conceptual structures which students use to approach electric and magnetic fields. Previous work in the field, though sparse, has confirmed that there are important conceptual problems common among students. The current study aims to give an integrated picture of the conceptions which two individual students applied across the range of contexts dealing with electric and magnetic fields and related phenomena; it does so working from within the framework of the SOLO (Structure of the Observed Learning Outcome) Taxonomy.

The theoretical framework

The SOLO (Structure of the Observed Learning Outcome) Taxonomy is the theoretical framework used for this investigation. The Taxonomy has undergone a continuous process of change since it was described in an article by Biggs and Collis (1980). It remains a system for classifying student responses into levels according to the quality of understanding displayed, but the sophistication and number of these levels has continued to increase. The Taxonomy's levels of understanding are arranged into cycles of learning within major modes of understanding. Of particular interest to this paper is the contrast between the Concrete-Symbolic and Formal modes of response; this distinction is a matter of current interest, as it was only touched on in the original textbook on the subject.

Biggs and Collis (1982) wrote the original textbook on the SOLO Taxonomy. This described four basic levels of classification for student responses: Unistructural, Multistructural, Relational and Extended Abstract. A Unistructural response gives one relevant fact, a Multistructural response gives more than one, a Relational response ties together a number of facts, and an Extended Abstract response introduces abstract principles to explain the facts. These levels were intended to describe outcomes of students' school learning in the context of a wider learning cycle, which took place across modes of functioning: Sensori-motor, Ikonic, Concrete-Symbolic, Formal. Learning was considered to take place by the individual passing through a cycle of Unistructural, Multistructural and Relational responses in each mode in turn, with the shift to Extended Abstract being the point where the next mode of functioning was achieved.

This rigid transition between modes of functioning has since been revised. Pegg (1992) and Levins and Pegg (1993) described multiple cycles of learning within the Concrete-Symbolic mode of the Taxonomy; that is, progress from a Relational level within this mode did not necessarily involve achievement of the Formal mode. This use of multiple cycles within modes increases the flexibility of the Taxonomy, and makes it possible to describe greater levels of subject-specific structure in students' responses. It also complicates the issue of defining the boundary between the Concrete-Symbolic and the Formal modes of understanding within the Taxonomy.

Most of the work done using the SOLO Taxonomy has focussed on responses in the Concrete-Symbolic mode, and to a lesser extent, in the Ikonic mode. The defining features of Formal responses are not yet clear, although the recent papers described in this paragraph have given findings in that direction. Pegg and Coady (1993) reported on university students' responses to mathematical problems; they described cycles of learning within the Formal mode, and identified Formal responses with an ability to consider conditions and constraints in their mathematical problems. Stanbridge (1993) described the use of SOLO in her science classroom, identifying Formal thought with the use of abstract models to answer questions, as opposed to use of algorithms. Guth and Pegg (1994), in their study of student understandings of patterns in iron filings, identified Formal responses with the ability to answer questions without assuming that all concepts were directly drawn from concrete reality. The current paper describes responses from two individuals who responded mainly from the Concrete-Symbolic and Formal modes respectively.

This paper comprises a detailed consideration of responses from two students; in general, the SOLO Taxonomy does not focus on description of overall development of individuals. A SOLO level is not a general statement about the individual along the lines of an IQ score; rather, it is a statement about the individual's understanding of a specific topic, analogous to a score from a test about electric and magnetic fields. An individual would be expected to display different SOLO levels for different topics in the same way as his or her scores would vary across different test items. Collis and Biggs (1991) emphasised that it is normal for individuals to display "multi-modal functioning," where skills from a range of levels are brought to bear on the same problem. This paper considers SOLO levels displayed by the individuals in their responses a range of questions.

The SOLO Taxonomy is still developing, with investigations into its levels and modes of classification. Of current interest is the nature of the distinction between Concrete-Symbolic mode and Formal mode responses. This issue formed one of the research questions for this study.

THE STUDY

There were two complimentary research questions treated in this study; firstly, to characterise students' conceptions of electric and magnetic fields, particularly the interactions between conceptions in the students' minds, and secondly, to identify characteristics of answers in the Formal mode of response as opposed to the Concrete-Symbolic mode within the SOLO Taxonomy. These questions were investigated using the following methodology.

Method

The two students described in this paper were selected from a body of students who completed a range of written and interview questions; these students were all enrolled in a first-year calculus-based physics course for which the pre-requisite was a good performance in high-school physics. Fifteen students completed the full range of instruments for this project.

The instruments of data collection were a written test, transcribed interviews and answers to assessment tests set by the physics department. A total of twenty-five questions were asked of each of the students; these questions were then analysed separately by finding "natural" groupings in the answers which were then described in terms of the SOLO Taxonomy. For an example of one of these questions, student responses to it and the technique of analysis, see Guth and Pegg (1994), which reports on responses of all the students to a single question from the battery. The work done in the current paper is intended to integrate the responses by study of individuals' responses to the range of questions.

The two students described here completed all the questions in the battery; these students were selected to give a view of the range of students doing the course, and particularly throw light on the nature of the SOLO Taxonomy's modes of functioning. Student 1 was selected as giving a large number of Concrete-Symbolic answers and was in an approximately median position in the data set, both in terms of test scores and levels of qualitative understanding displayed. His answers are of interest in that they are representative of difficulties which the majority of students were having with this material. Student 2 gave a large preponderance of answers in the Formal mode, and was selected for this reason, to contrast with student 1.

The transcripts of these students were then read and summarised, with the summaries being further broken down; the aim was to integrate the responses of each student across the range of 25 questions asked. Descriptions of each of the students in turn follow.

Results

Student 1

This student's answers, like those of most of the students tested, tended towards the Concrete-Symbolic mode of response. He lacked the broad overview which was demonstrated by student 2, who operated mostly in the Formal mode when dealing with this topic. His level of response was typical of the students sampled, making his responses of particular interest for considerations of learning and teaching in this subject.

Speaking in broad terms, Student 1's grasp of field representation was unclear and not entirely consistent, as will be elucidated at length in a section 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 still 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 results for the student's understanding of phenomena related to fields. His predictions of particle movement in fields were accordingly affected, as was his reasoning about phenomena occurring in open electric circuits and the fields associated with them.

Student 1's grasp of field representations

This student's ideas of field representation were based on a Concrete-Symbolic picture of "field lines." His ideas of the field vector and field strength at a point were also 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.

Field lines were generally seen by this student as concrete entities, across a variety of contexts. 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 dominated by field lines. Given a situation where two charges are producing an electric field and asked where the field strength would be maximum, he replied:

> 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.

One sees here that his ideas of interactions between fields were based on a vague intuitive picture of "combining," with strengths of fields simply adding together.

> Interviewer: OK, 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 were paramount in the above, and as a result, the student was unable to make any specific predictions.

The student had some ability to work with the field strength vector when specifically asked to do so, 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: OK, 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.

Here, the student was drawing components relative to an arbitrary axis. While this operation is relevant to the mechanics of calculating using vectors, he has still missed the more abstract points about the reasons for using vectors. Although he did use a test-charge picture, there is a Concrete-Symbolic emphasis on the mechanics involved. The student also had trouble with quantitative reasoning based on the concept of field strength at a point and resultant force on a charge. In fact, the concept of field strength was not clearly separated from the concept of potential in a field, with identical predictions for both quantities.

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: OK, 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, the student was unable to use the concept of potential and relate it to kinetic energy in the context of particles moving in fields. That is, he was aware of the Concrete-Symbolic definition, but there was no connection to the rest of his knowledge.

As part of the general vagueness about representation of fields, there was 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. This confusion between electric and magnetic fields seems likely to make it impossible for the student to clearly grasp the scientist's picture of induced currents, where both electric and magnetic fields are involved and interact with one another.
Overall, this student's grasp of field representation was an attempt to hold things together by Concrete-Symbolic "rules of thumb," rather than come to a full Formal-mode overview of the system of field representation in physics. This piecemeal approach has implications for his understandings of phenomena related to fields.

Student 1's grasp of related phenomena

Related to the unsystematic representation of fields was a corresponding difficulty with predictions about phenomena resulting from fields. Particle movement in fields was poorly understood for reasons arising directly from difficulties with field representation: predicted trajectories of single particles in fields were overly simplistic, due to excessive reliance on field lines and dim 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 was resistant to an argument using the direction of force in this situation to show that the particle could not follow this line exactly. This belief, although not strictly accurate, was held by the majority of students surveyed. He was also unable to relate voltage, potential and kinetic energy in an electric field, when presented with problems which involved making this connection.

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. Movements of individual charges in fields presented problems for this student.

Movement of a bulk of charges in electric circuits was 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 be likely to happen in the circuits. That is, his reasoning was not based on particles in this case. There is the implication that teaching based on a particle model may not be appropriate for the bulk of students. This student was unable to use the particle model either where the currents were caused by electric fields, or where they were caused by induction of current due to movement in magnetic fields.

> Interviewer: OK, 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 very simplistic, and poorly defined. Particles played no role in the causation picture, being added in later. Where an open circuit and transient current was involved, this student predicted that current would flow until the particles ran out. This prediction failed to allow for the effect of the fields of the moving charge, which would stop charge movement well before the charged particles actually ran out. The implication of this prediction is that the student was failing to see feed-backs between the field causing charge movement and the field of the moving charge. This kind of feedback is more typical of a Formal mode overview of the topic, as seen in student 2's responses.

Overall comments on student 1

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 idea was somewhat compartmentalised in his mind. His grasp of field representation was based on concrete concepts, primarily field lines. This grasp of field representation had outcomes for his comprehension of field-related phenomena. Specifically, there was a failure to see the feedbacks involved in the movement of charge in fields, and difficulty using the abstract concept of potential in considerations of energy in fields. This student, answering in the Concrete-Symbolic mode, lacked the striving after meaning in the context of an abstract framework which we see in the responses of the next student, who answered primarily in the Formal mode of the SOLO Taxonomy.

Student 2

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. The answers show a concern with consistency and overview that was lacking in student 1's responses.

Student 2's grasp of field representation

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 picture, but they were seen in light of their formal definition, and were divorced from any need for directly observable concrete ideas. Compare his response about the lines in iron filings around a magnet to that of student 1 above. An example of a

Relational Formal response which also appears in the author's previous paper (Guth and Pegg, 1994) is:

> 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, a number of points are clear. Firstly, 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 trajectories followed by particles in a field, but could make the more abstract statement above, which is a Formal-mode representation of ideas.

In the above, we also see the idea of local field direction at a given point, integrated with the student's picture of field lines. The student was able to work with the idea of field strength at a point, both in the above, and in more quantitative questions. This student was more comfortable with the idea of potential in fields, but still had trouble relating it to field strength.

The difference between electric and magnetic fields was clear and consistent in all this student's responses. When asked to explain the distinction he did so in quite abstract terms:

> 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 of the student. 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. The distinction between electric and magnetic fields in this response is validated in the light of his responses to a range of concrete questions involving various aspect of this distinction.

Student 2's grasp 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; while movement of bulk charge within conductors took full account of the fields caused by the moving charge.

Single charges moving within electric and magnetic fields were generally handled skilfully, with the clear distinction between electric and magnetic fields making accurate predictions possible where these were involved. 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.

This student 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.

This student was generally able to see the connection between currents and fields on the one hand and charged particles on the other. 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 - is going to be the direction that the charge is moving, and that's all that a current is...
> Interviewer: OK, 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.

This student was able to make accurate predictions about phenomena related to fields, with an overview of the system involved.

Overall comments on student 2

Student 2 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. His constant search to connect all the pieces of information in the context of an abstract system was highly characteristic of the Formal SOLO mode.

CONCLUSION

These two students show 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 contain elements of all the modes of the SOLO taxonomy. These two students have been selected because their tests and interviews each contained a large proportion of responses characteristic of the Concrete-Symbolic and Formal modes, respectively. For the purpose of clarity in this paper, their thinking in other modes than the one being illustrated has not been emphasised here.

The Concrete-Symbolic representation of fields used by Student 1 has a number of implications for those designing learning experiences in this area. Student 1 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 had with the material are likely to be common to most physics students, particularly at school level. Student 1's difficulties and tendency to concrete ideas are a useful guide for educators.

Student 1 had difficulty relating to abstract concepts of field lines and tended to see them as more concrete entities, particularly as paths followed by particles in the field. This was a very common way of thinking for the first-year university students surveyed. An implication for teaching is that it may be best, particularly at lower levels of study, simply to accept this picture when first introducing students to 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 student 1 also did not clearly involve particles in reasoning about phenomena. While particles were used in descriptions, they seemed to be "tacked on," 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 student 2's responses; however, student 1 was far more typical of the class studied. 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 student 1's Concrete-Symbolic responses were typical of the class surveyed, student 2's Formal responses were exceptional. Student 2'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.

Student 2 was able to explain phenomena in terms of charged particles where this was appropriate, fitting charged particles into a general network of relationships between electro-magnetic phenomena. Where student 1 was incapable of using a charged particle picture, student 2 was able to do so; however, it must be borne in mind that student 2 was exceptional, and student 1's difficulties were typical of the university students surveyed. Student 1, with his Concrete-Symbolic view, was most useful as a guide to planning of instruction in this area; student 2 is interesting as an example of Formal mode responses in about the area.

Comparison of the two students described in this paper 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 the context of student 1'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.

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APPENDIX C

Preliminary concept maps.

A number of concept maps were produced before the pilot data collection. They are given and explained in this appendix.

PRELIMINARY CONCEPT MAPS

Concept maps have been a feature of the study from its inception, being used as a tool to guide the researcher rather than as instruments for data collection. Concept maps were created before the design of both pilot and main instruments. This section describes the evolution of the concept maps which preceded the pilot studies. The concept map which was produced after the pilot studies is included in chapter 3.

In order to clarify the ideas of the researcher prior to creation of pilot test instruments, concept maps were made of ideas concerning electricity, magnetism and electromagnetism. The procedure was as follows: Numerous physics problems based on the New South Wales Higher School Certificate electricity and electromagnetism core units (Science Teachers' Association of NSW, HSC revision questions, 1992; physics curriculum by NSW Board of Senior School Studies, 1979) were analysed in terms of the components of knowledge required for their solution. The Higher School Certificate was relevant because the majority of students in the class under study would have done the HSC course the previous year. The relevant chapters of the course text (*Physics for Scientists & Engineers with Modern Physics* (second edition), Giancoli, 1989) were read, and used as an additional source of concepts for inclusion into a concept map. These components of knowledge having been identified, a concept map was then constructed using all of them.

The general structure of this first concept map is shown in figure C.1. In this figure, there is a general division into the three groups electrical, magnetic and electromagnetic on the one hand, and the two classifications of qualitative and quantitative on the other. Mathematical concepts were included as a separate grouping. The colour coding of the scheme is as follows: electrical in green, magnetic in red, electromagnetic in blue and mathematical in black. When this general plan for the concept map was then filled out with all the elements previously identified, the result was of great complexity, as shown in figure C.2.

Figure C.2 is an attempt to show all the detailed elements of knowledge, linked by arrows. The colour codings are the same as for the first figure; as well, elements have been placed in areas of the page corresponding to the topic areas in figure C.1, where this did not excessively lengthen the connecting arrows required. While figure C.2 does give an idea of the links between specific elements of knowledge, its complexity makes it hard to use. The level of detail in figure C.2 seems to make it less useful for giving broader ideas of how groups of concepts relate to one another. As the reproduction of figure C.2 in this thesis is rather hard to read, details of its contents have been included on the pages following it. These detail diagrams, while not showing all the connections in figure C.2, do include all the elements from that figure, and serve to present figure C.2 in a legible and clarified form.

Figure C.3 shows another concept map, where these same elements have been arranged without arrows, and conceptual relatedness is indicated by relative positions on the page. Colour coding has been used again to show the groupings of figure C.1. While the approach of figure C.3 does not allow the more complete set of interconnections between concepts seen in the second figure, it is considerably easier to read. As the reproduction of figure C.3 in this thesis is also rather hard to read, the elements used in figure C.3 are listed on the pages following it, grouped according to conceptual relatedness. Figures C.1, C.2 and C.3 were productive of research questions.

The explicit nature of the structure shown in the figures helped to define the author's ideas about likely ommissions in the knowledge structures constructed by students: for example, the question of whether students would construct the link between field vector and field lines shown in figure C.2. Also, figures C.2 and C.3, due to their relatively exhaustive coverage of the topic areas of electricity, magnetism and electromagnetism, helped to ensure that no important facets of the topic areas were left out of consideration in the construction of the pilot tests.

The concept maps discussed in this appendix were produced before the pilot studies, and served to guide construction of questions for these studies. Another concept map was produced after the pilots based on fewer key elements. It reflected the researcher's view of the topic, and was useful in formulating final research questions. This final map is given in chapter 3 as figure 3.1.

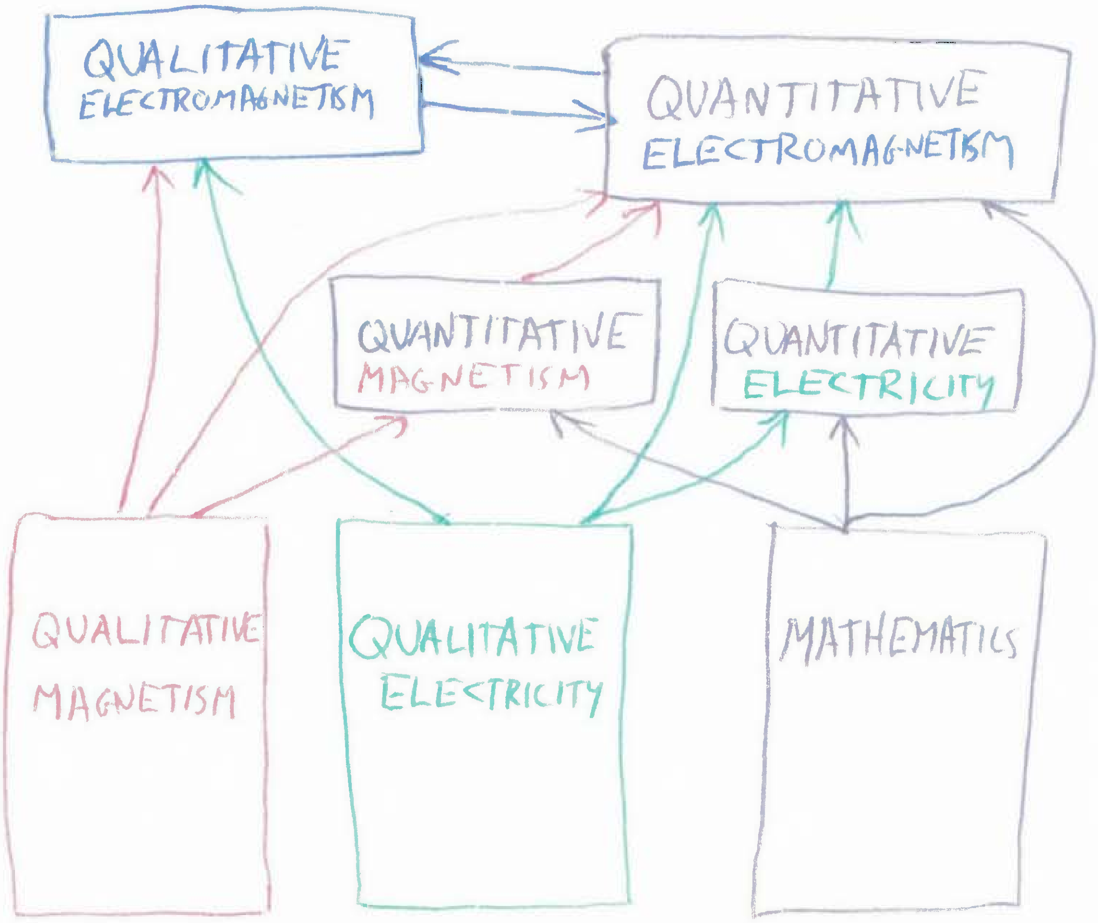


Figure C.1 Broad-scale concept map

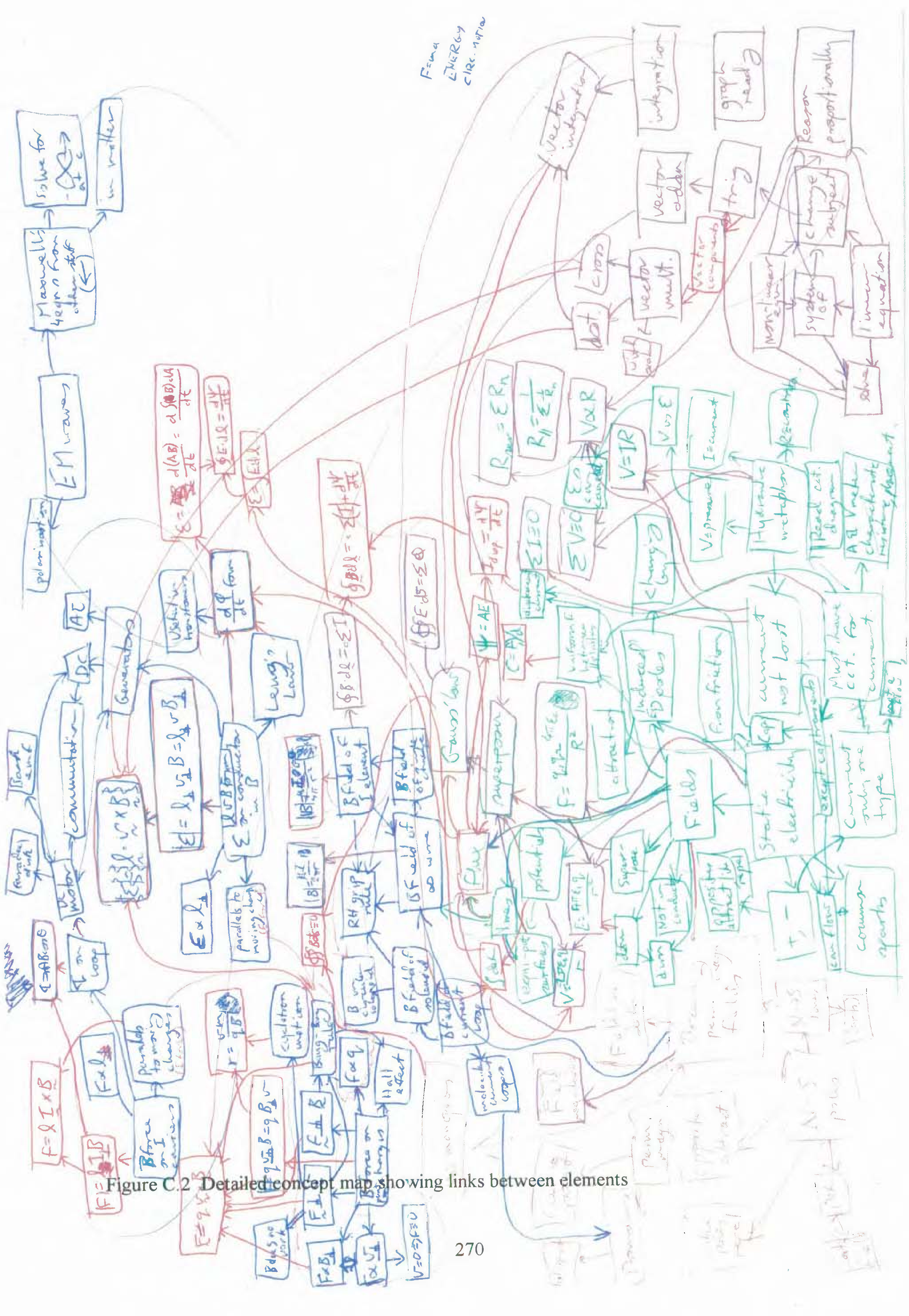
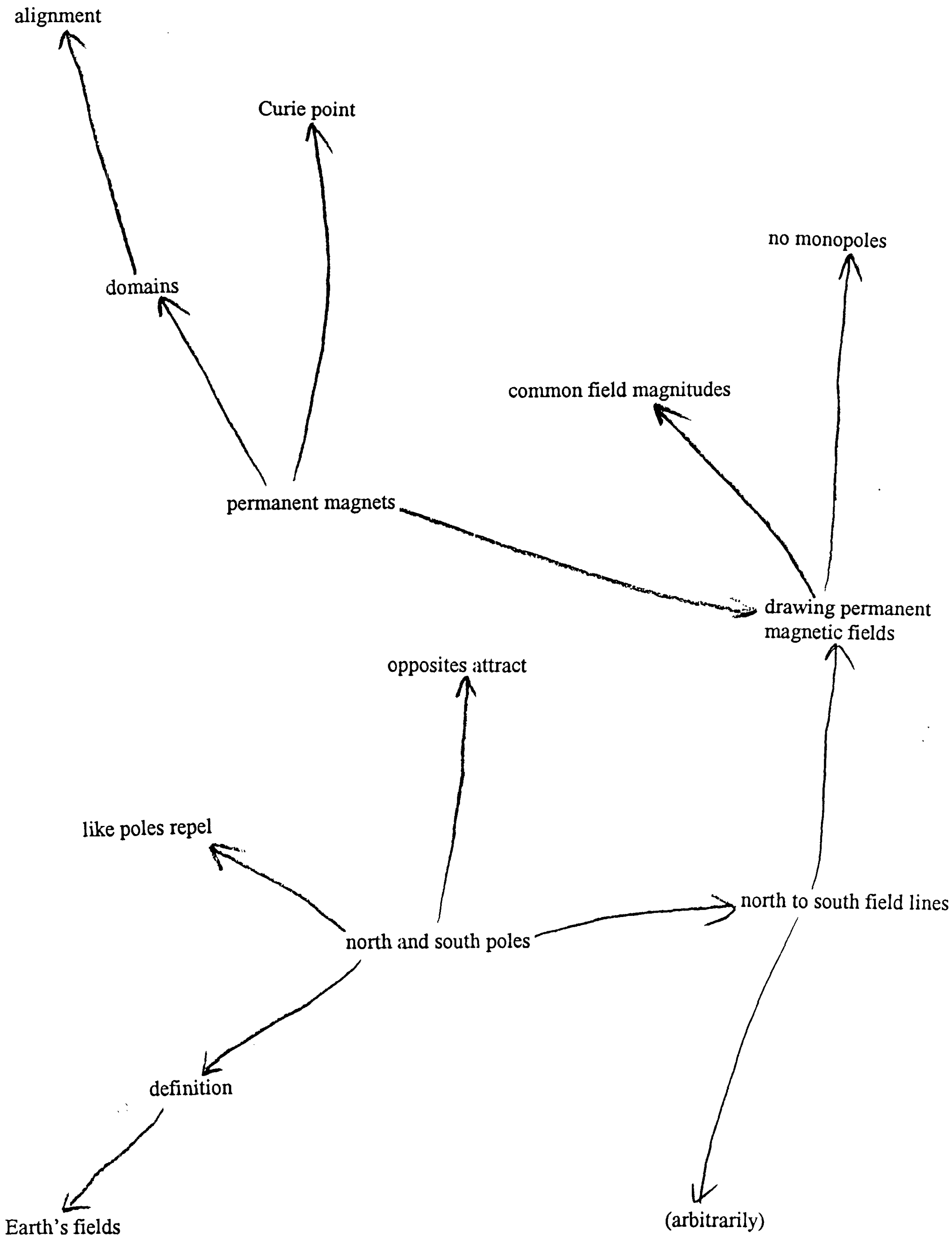
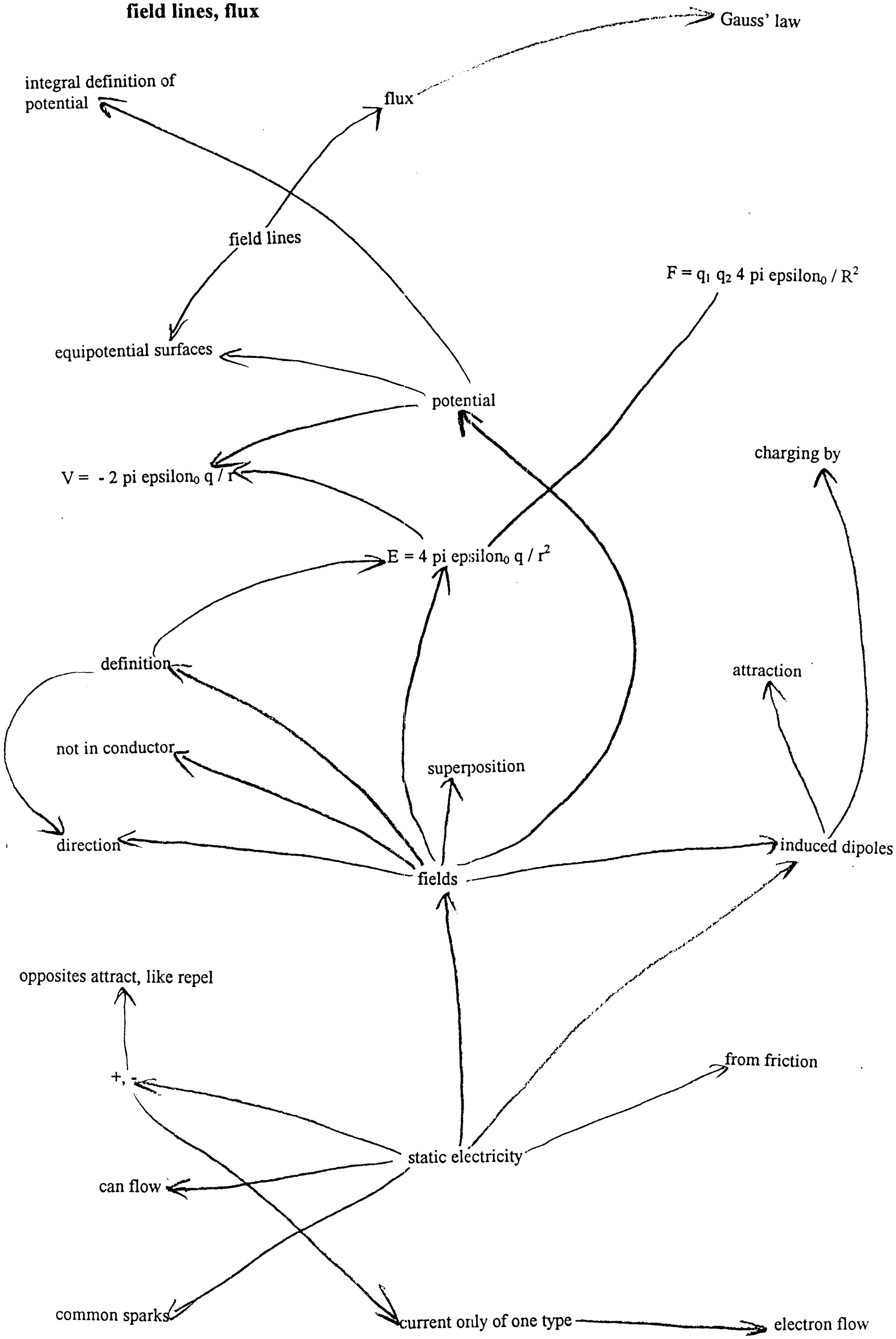


Figure C.2 Detailed concept map showing links between elements

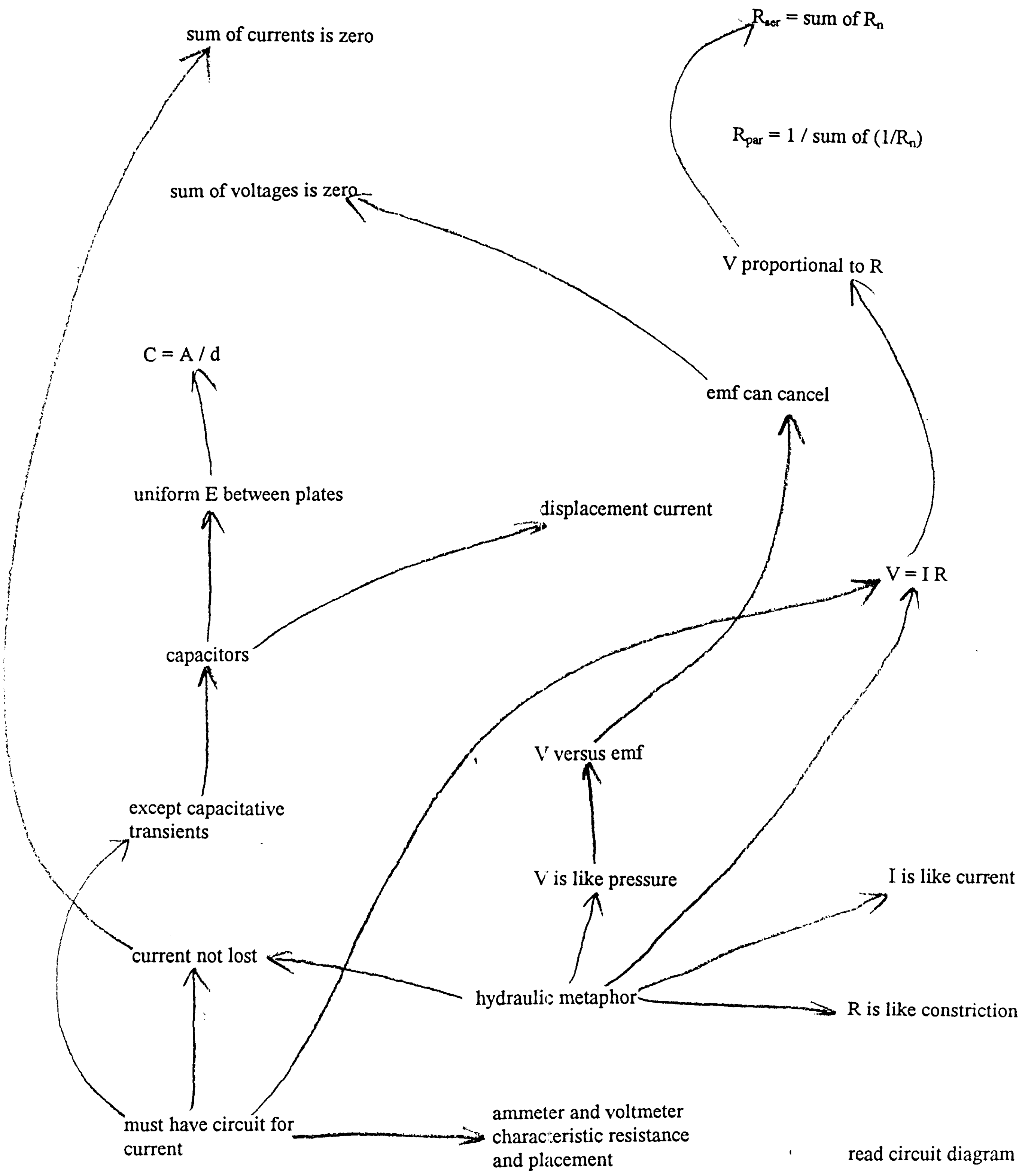
Detail of red part of figure C.2: Magnetism, north and south poles, magnetic fields



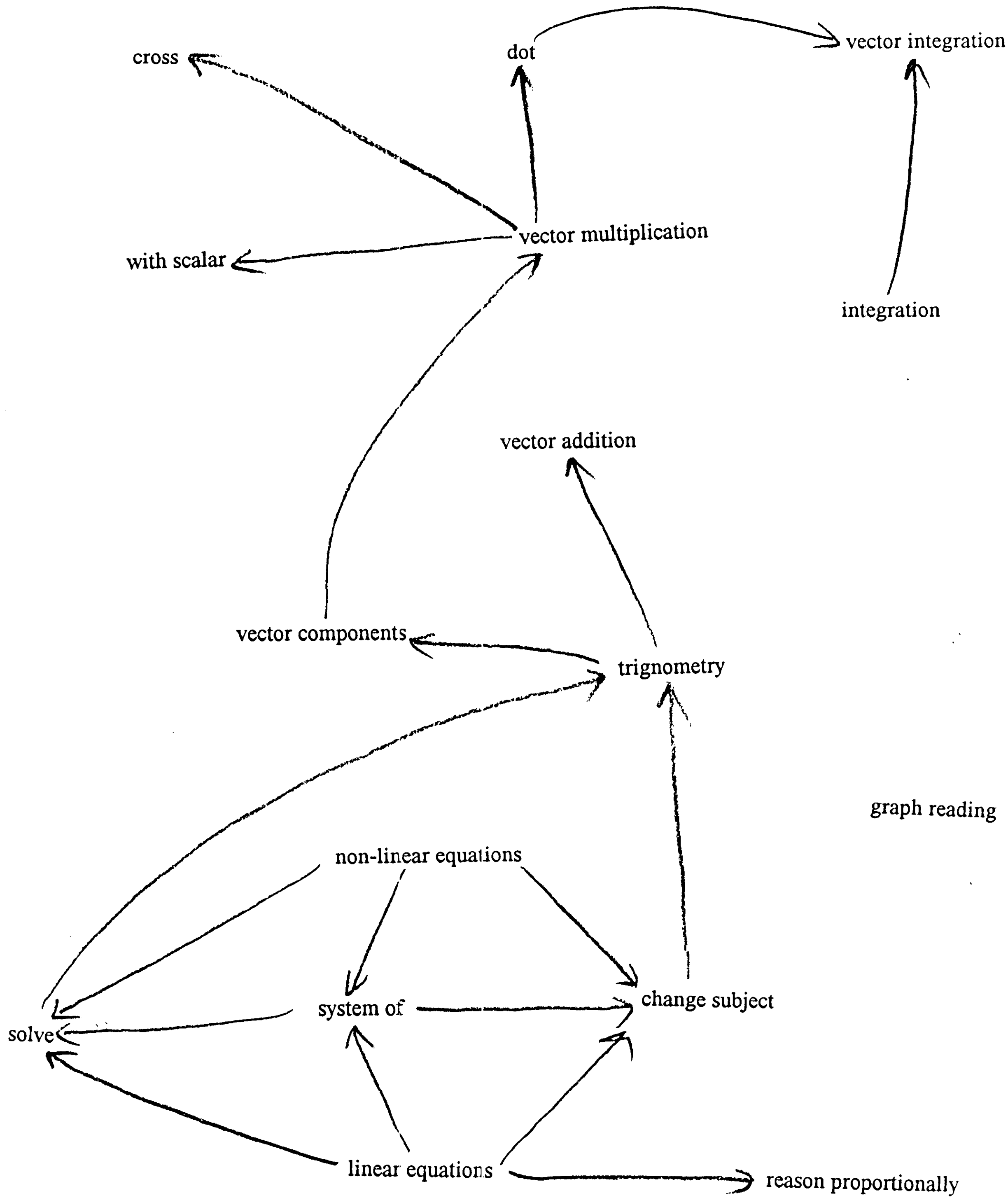
Detail of left half of green part of figure C.2: Static electricity, fields, potential, field lines, flux



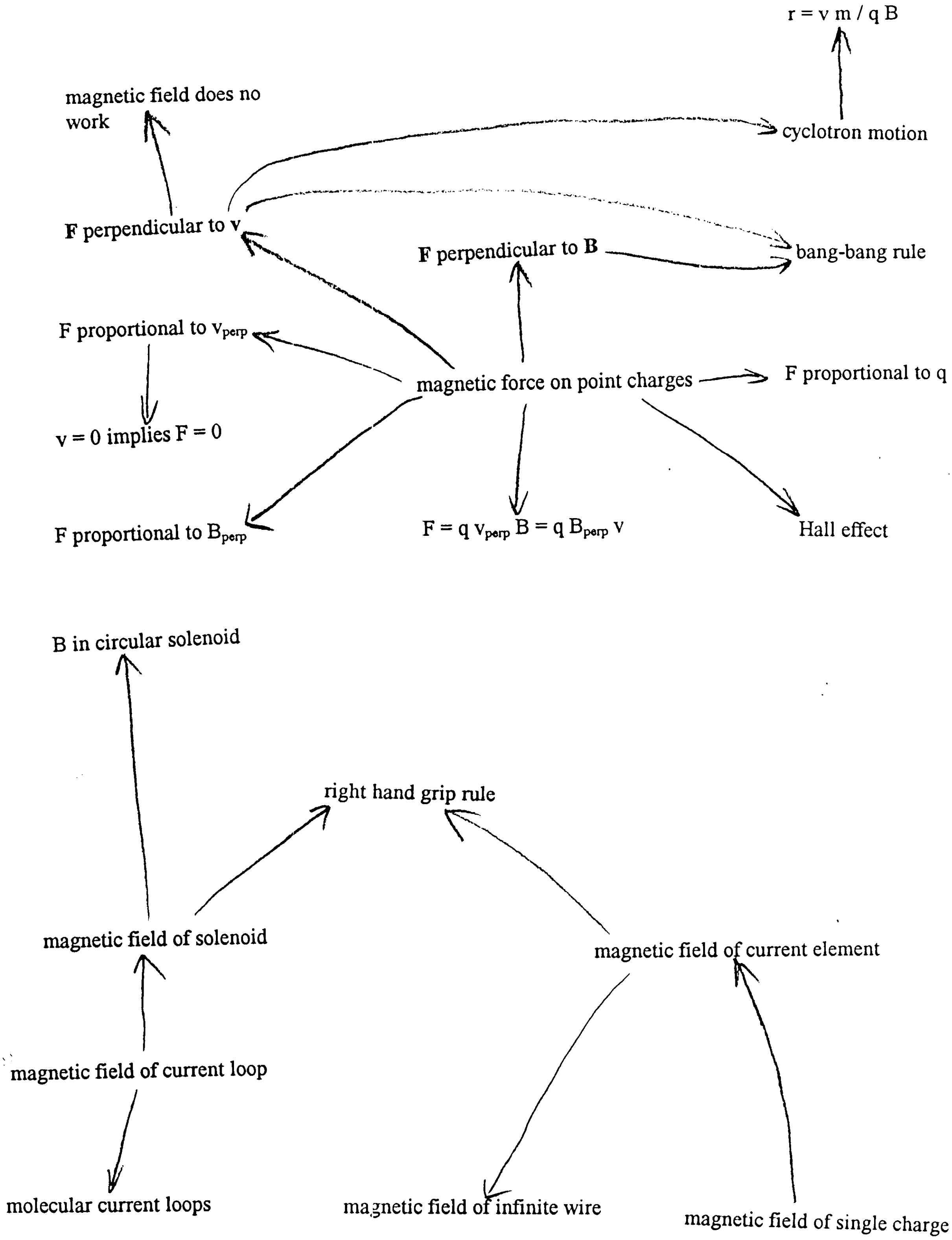
Detail of right half of green part of figure C.2: Current, hydraulic metaphor, capacitors, voltage



Detail of black part of figure C.2: Mathematics, algebra, solution, vectors



Detail of left half of blue part of figure C.2: Magnetic effects of charge, magnetic effects on charge



Detail of right half of blue part of figure C.2: emf, generators, motors, electromagnetic waves

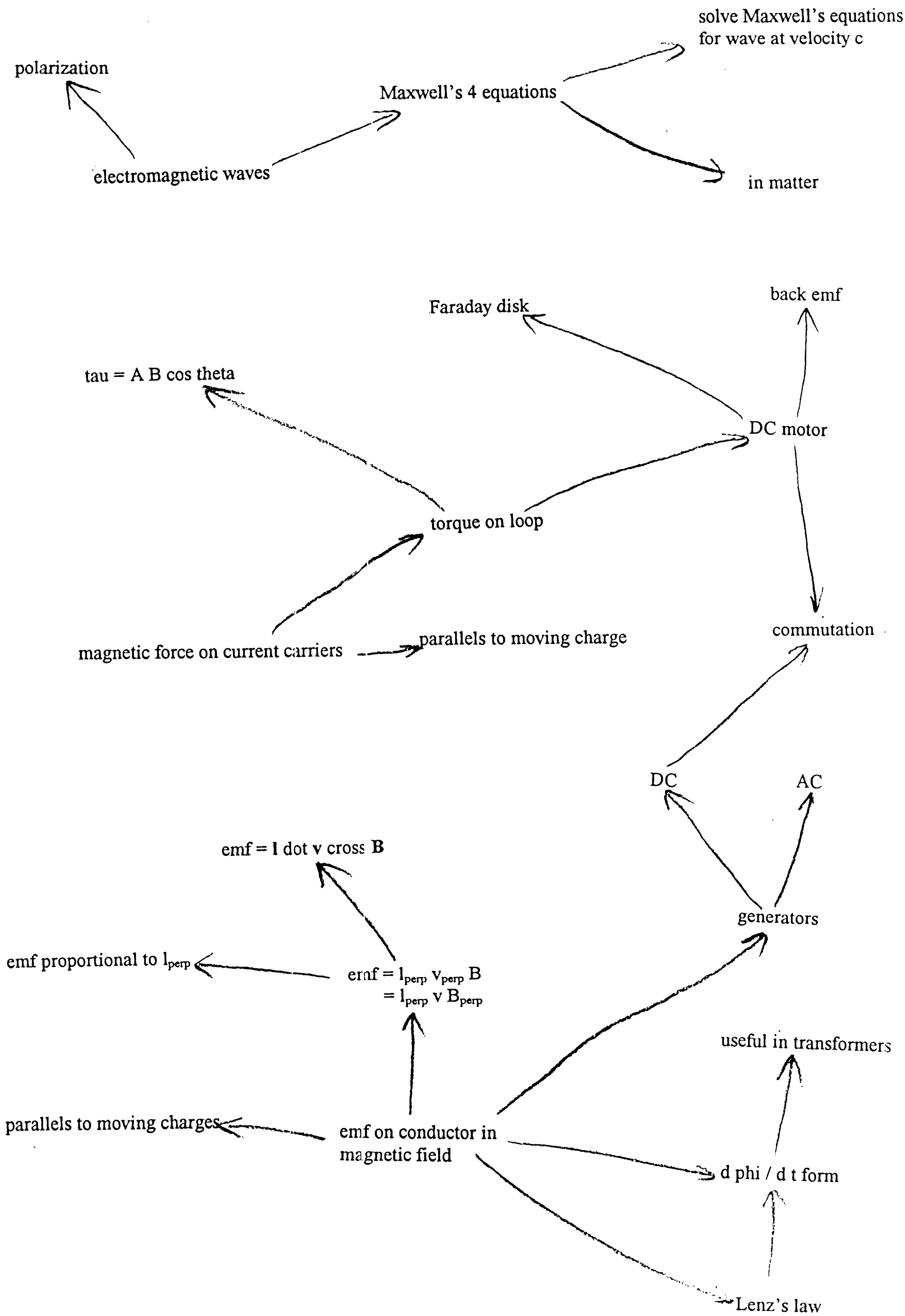


Figure C.3 Concept map with elements grouped by subject

List of elements appearing in figure C.3

PERMANENT MAGNETS:
induced domain alignment
Curie point
permanent magnets
domains
molecular current loops
north-south poles
north to south field lines
drawing typical magnetic fields
typical magnetic field values
like poles repel, opposite attract
no monopoles
definition of north and south poles

FIELD REPRESENTATION
fields
field-at-a-point
test charge
F = q **E**
field superposition
field lines
flux equivalent to number of field lines through a surface
field line density proportional to E
V m^{-1} = N C^{-1}
flux = E A = "psi"
Gauss's law
using Gauss's law for a point charge
Gauss's law in integral form
Gauss's law for magnetic flux
E proportional to 1 / r^2 for point charge
E = 4 pi $epsilon_0$ q / r^2
no electric field in a conductor
charging by induction
induced dipoles
potential
V = PE / q
equipotentials
equipotentials perpendicular to E
E = dV / dn
V = integral E dn

CAPACITATIVE PHENOMENA
static electricity
+, -
sparks
capacitative transients
capacitors
capacitors as energy storage
C = A / d for parallel plates
uniform electric field for parallel plates
displacement current in capacitor
I_{disp} = $epsilon_0$ dpsi / dt

CIRCUIT ELECTRICITY
current
reading circuit diagrams

"topological" nature of circuit diagram
using an ammeter, voltmeter
only one type of current
conventional current not electron flow
water in pipes metaphor
$V = I R$
$P = V I$
$P = V I = I^2 R = V^2 / R$
V as potential difference
V versus emf
sum of voltages = emf in circuit
Kirchoff rule: sum of voltages = 0 for loop in circuit
current sources versus emf sources
ideal battery as voltage source
R_{series} = sum of R
$R_{parallel}$ = 1 / (sum of 1/R)
I proportional to 1/R for components in parallel
V proportional to R for components in series
light bulbs are non-ohmic

MATHEMATICS
proportional reasoning
linear equations
change subject
system of equations
non-linear equations
integration/differentiation
graph reading
trignometry
vector components
vector addition
vector dot-product
vector cross-product
vector integration /differentiation
unit prefixes
equations of motion under constant acceleration
$F = m a$
$F = m v^2 / r$

PARTICLES AND CURRENTS IN MAGNETIC FIELD
magnetic force on point charges
bang-bang rule
$F = q v_{perpedicular} B = q v B_{perpendicular}$
F perpendicular to **v**
F perpendicular to **B**
v = 0 implies magnetic F = 0
magnetic field does no work
change in velocity = 0 for pure magnetic field
F = q **v** cross **B**
Hall effect
cyclotron motion
$r = m v / q B$
T = 2 pi m / q B
$F = l I B_{perpendicular}$
torque on loop
F = **l I** cross **B**
torque = I A B cos theta
DC motor

commutators
coil turns to maximise included magnetic flux
force on parallel wires attractive for parallel current direction
$F = l\ (mu_0 / 2\ pi)\ (I_1\ I_2 / r)$

MAGNETIC FIELDS OF CURRENT
magnetic field of infinite wire
symbols for field into and out of page
right hand grip rule
$B = (mu_0\ / 2\ pi)\ (I / R)$
magnetic field of single charge
magnetic field in linear solenoid
magnetic field in circular solenoid
magnetic field of current element
domain alignment in electromagnets steel cores
hysteresis in iron cores
integral of $B_{parallel}$ dl = mu_0 I
vector integral around a closed curve **B** dot d**l** = mu_0 I

GENERATION OF CURRENT
emf = $l_{perp}\ v_{perp}\ B = l_{perp}\ v\ B_{perp}$
bang-bang rule
emf = **l** dot **v** cross **B**
emf = - dphi / dt
transformers use dphi / dt
$V_{primary} / V_{secodary} = n_{primary} / n_{secondary}$
Lenz's law
self-inductance
generators
Faraday disk dynamo
commutation arrangements AC/DC
AC generator
back emf
full sinewave every cycle
electromagnetic waves
polarization of electromagnetic waves
solve Maxwell's equations for transverse waves

APPENDIX D

Pilot studies.

A number of pilot studies were undertaken before the main data collection, with the idea of refining written and interview questions, and gaining a preliminary understanding of the conceptual issues facing students. They are described in this appendix.

PILOT STUDIES

This appendix contains the results and test papers for the pilot testing which preceded the main study. Pilot studies took place after preliminary concept mapping, which is described in detail in the preceding appendix C. Concept mapping gave a framework for the topic material under investigation, and played an important role in the design of the pilot instruments. Aims of the pilot investigations were two-fold: there was the intention of exploring general student understandings of topic areas, coupled with the wish to refine specific questions and means of questioning.

Pilot testing allowed identification of interesting issues in students' conceptual development, as well as improvement of test questions and their style. These studies involved a preliminary investigation of students' concepts to focus the deeper investigation of the main study. The concepts to be investigated were those set out at the end of chapter 1, coming out of the literature survey of electricity and magnetism. As well as a preliminary investigation of the concepts, there was also a need to improve the form of questions in the instruments.

The pilot testing allowed questions to be tried out before the main study, to determine which questions were most effective. There was also an interest in refining interview technique, and the use of prepared scripts in interviews.

This appendix describes the three rounds of pilot testing which took place in late 1992 and early 1993. Each of the three sections that follows deals with one of of the rounds of pilot testing. The description of these pilots is structured around the student concept areas investigated in them.

PILOT 1: YEAR 11 PHYSICS STUDENTS

A Year 11 physics class was tested in November 1992, at the end of the school year. The class was working from the New South Wales Higher School certificate 2-Unit Physics course (Board of Senior School Studies, 1979), and had just completed an "electrical interactions" unit (Core D of this syllabus), but had not started the "electromagnetism" unit (Core E). Therefore, the scope of questions in the instrument was confined to independent electric and magnetic phenomena.

The test given appears at the end of this appendix, with each question from the test along with a statement in italics about the goals of that particular question; this information as to goals was not given to the students in their test papers.

Methodology of Pilot 1

The written test was delivered during a physics lesson in November, 1992. While the test was designed to take fifty minutes, unforseen changes to the timetable for that day meant that only thirty minutes were available. The test was taken under examination conditions. Ten students were present.

On the following day, two students were separately removed from class to be interviewed about the test. During December of 1992, the written test was administered to two Year 11 students from other schools, and one of whom was interviewed; this interview was transcribed also. The next section is an exposition of results from the written test, followed by a discussion of interview methodology and results.

Results from the written test in pilot 1

The students responses revealed some alternative conceptions and areas of difficulty for the students. It was also possible to assess the effectiveness of each of the questions in revealing students conceptions. Below, the outcomes of the written test are dealt with by section of the test.

Fields

These questions showed that students did have trouble with the ideas of fields, particularly field lines. The question asking students to calculate field strength, given force on a charge and magnitude of the charge gave a poor range of response and no verbal explanations. The question concerning equipotential lines received a poor range of response, as students showed a lack of any understanding about the nature of equipotential lines at all.

Vectors

In the vectors section, students seemed to be generally able to add vectors, although they had trouble with components. It may be best, for later tests, that questions specifically about vector use be replaced with questions using vectors in field situations, for more efficient use of test space.

Proportional reasoning

Roughly half (5) of the students were able to answer this question. As with vectors, it may be best that use of proportional reasoning be tested in questions with a field context in later tests.

Magnets

These questions revealed a complete confusion between electric and magnetic fields in students' minds. The questions asking for definitions and descriptions of terms produced simple and/or rote-learned answers. Student responses to the question about lines in iron filings near a magnet did not attempt to explain the mechanism which causes these lines -the addition of "explain why the iron filings don't just go straight to the poles of the magnet" to the question arose from this.

Circuit electricity

Students showed a poor understanding of the concept of voltage here, as well as of electrical energy and current. It seemed reasonable that questions about circuit electricity per se be dropped from later tests, due to their relatively peripheral nature to the interest of the study, which is towards field-related phenomena.

Summary of outcomes of written test

A number of questions were marked for exclusion or modification as a result of their inclusion in pilot 1. A clearer picture of students' conceptions was also gained. While data were too sparse to indicate SOLO levels, a number of important points were indicated about the students' understandings of field concepts, mathematical concepts, magnetic fields and circuit electricity.

Post-test interviews

Three students were given post-test interviews. Two of these were from the main class, and could only be interviewed for approximately 15 minutes each. The third interview, lasting 40 minutes, was with the student outside the class who displayed a good understanding of the written test. Interviews aimed mostly to clarify unclear answers in the subjects' written tests. The short length of the interviews made it impossible to introduce new material in them. Questions asked were questions of clarification about what students had written. Full transcriptions of the interviews were later done to aid analysis.

Interview transcripts gave a clearer picture of the students' ideas, as shown by quotations from them - below, these students' ideas about field lines are described from their interview transcripts.

The first two interviewees had difficulty with the abstract nature of field lines. The first student interviewed (S1) identified them with equipotential lines:

> *Interviewer: Where would the field line be?*
> *S1: It would be here [drawing], it'd be around it, right round the source.*
> *Interviewer: Ri-ight [pause] Would it have anything to do with these equipotential lines you drew here?*
> *S1: Yeah, isn't that them?*

This student also thought of field lines as boundaries between different levels of charge:

> *Interviewer: What exactly do you mean by "the field lines are boundaries?" What's on each side of the boundary.*
> *S1: A different, uh, level of charge. Say, one side could be a hundred volts, the next one could be eighty volts. And as you get further away from the source, it gets, the charge level gets, lower.*

The second student (S2), had a more conventional idea of electric field lines, "a field line is the direction in which a charge is attracted to a positive charge", but still seemed to have a picture of distinct lines separated by spaces.

> *Interviewer: What's in the space between the field lines?*
> *S2: Um, space I guess, I dunno [pause] um the difference between um where the electrons are being run, I guess.*
> *Interviewer: So it's -*

S2: [pause] There's something there, but it's actually attracted more heavily there, that's all, so the electrons actually go there.

This student did not assume that a test charge doesn't affect the field, which gives a complication when considering field lines and their effect on a test charge.

S2: But the field line is determined by the test charge - I think, anyway. Probably wrong, but that's what I reckon.
Interviewer: You mean something like you drew here, so it actually changes the field.
S2: Yeah [pause] Like, you can't have the same field lines for when a test charge is there to when it's there, because, like the field lines wouldn't go up there if the test charge is there.

The third student, who was not a member of the main class, and had a significantly longer interview, seemed to show a good grasp of the idea in his statement about field lines:

S3: um, basically learnt about them, as in, how to draw them, like, the lines never cross and things because it's like, not [pause] We learnt that there aren't actually lines of stuff there, that's just a representation of it, there'd be an infinite number of lines in there.

Even so, he was not comfortable trying to explain exactly what field lines "really mean":

S3: I mean they [field lines] are a tool more than anything else, so we learnt how to use them rather than what they really meant.

During these pilot interviews, the students' answers on some topics, notably field lines, were made clearer. The results indicated that it was practical to clarify students written answers by a post-interview, and that their interview transcripts could usefully illustrate their answers. The procedure of written test followed by post-interview was an appropriate way to explore student understandings of this topic.

Comments on pilot 1

This pilot was useful in that it allowed the trialling of a number of written questions, some of which were marked to be discarded or modified for further work. A number of concepts among the students were also identified as worthy of further investigation.

Field concepts, particularly the concept of field lines, seemed to be presenting problems to the students. Students seemed either to excessively reify the "field lines" drawn in the diagram, or else not use field lines in their reasoning. They also had trouble with the mathematical problem in the proportional reasoning section, which has bearing on the developmental level of the students, as well as their likelihood of using analogous reasoning in their physics.

Magnetic fields were identified with electric fields by the students. No students were able to suggest any significant difference between the two - this confirmed Maloney's (1985) report that students tend to confuse electric and magnetic fields. No students were able to reason qualitatively about magnetic fields sufficiently well to explain the formation of patterns in iron filings near a magnet. Clearly, poor understanding of magnetic fields could cause difficulties in further study of electromagnetism.

In circuit electricity, the students displayed a certain vagueness about the concept of voltage, and had difficulty using it in qualitative questions about simple circuits. This is consistent with the literature on the topic, and seems likely to cause confusion in these students' later work on electromagnetism involving current and voltage.

The student concepts mentioned above acted as a guide for further investigation of the research questions. A need remained for further investigation of interview procedures and questions, which was the emphasis of pilot 2.

PILOT 2: INTERVIEWS WITH GRADUATES OF HIGH SCHOOL PHYSICS

This pilot took place in March 1993, and was intended to give data about understandings of electromagnetic concepts more advanced than those covered in pilot 1, which dealt with Year 11 students. The study of three individual students' understandings was an important feature of this pilot. Additionally, this pilot offered an opportunity to further develop an approach to interviewing.

Methodology of pilot 2

This pilot allowed a test of the case-study of individual students. Three students were involved here. Points of interest having been identified by preliminary concept mapping and the previous pilot 1 were noted down and used as the basis of a 40 minute interview with a graduate of high-school physics (subject A). No tape recording was made of this interview, but the subject made most of his answers in written form. After this, a list of questions was prepared (see end of this appendix) and used in taped interviews with two other graduates (subjects B and C). The tapes of these interviews, lasting 30 and 60 minutes, respectively, were not transcribed as such, but used to write summaries of the subjects' answers.

Results from subject A

In spite of 14 years intervening since he had completed high-school physics, and his lack of use for the topic during this time, subject A had considerable recollection of electricity and magnetism.

His idea of fields seemed to relate mostly to magnetic fields. When asked about electric or gravitational fields, he said that it seemed to him that "Gravitational field would be the space which under the influence of the attraction of that particular mass." He was unable to use any equations to describe fields, and seemed to think of fields as areas of influence. His understanding of field lines also seemed oversimplified, in that he believed that forces would not affect particles between drawn field lines.

He spontaneously recollected the existence of "right hand rules", but had difficulty applying them to a range of example situations. He wrote that "Right hand rule indicates the relationship between the vector of magnetic field, the electric field and the direction of motion." In a case involving motion of a charged particle through a perpendicular magnetic field, he predicted a force perpendicular to both, after some consideration of what would be electric field and magnetic field in this case. However, in a case involving a stationary magnet and an electron placed in the field around it, he predicted that the electrons would follow the field lines, without attempting to consider any right hand rule.

In summary, this subject had difficulty with abstract mathematical field concepts, as well as with the logic of the right hand rule and its application.

Results from subject B

Subject B had done 2 Unit Physics for the New South Wales Higher School Certificate, three years before the interview. She said that her mark for the unit was 96%. It was remarkable how her understanding of the topic seemed to have vanished completely in the intervening time. She was quite unable to answer questions about field lines, charge movement in magnetic fields, flux, magnetic fields of current, electric potential and potential difference. Asked: What is the right hand rule?, she placed her hand in an appropriate position and said "I can't recall which goes with which finger. I think this one was velocity, this was magnetic field, and this last one... oh, that must be electricity." This was an unusually detailed answer among her replies. In her statement "that must be electricity", her use of the general word "electricity" serves to give an impression of the lack of detail throughout her replies in general.

However, as she explained, "I studied physics just to get a good score in the HSC".

Results from subject C

Subject C did physics in the HSC (mark in the mid-80s) as well as the first year university physics course. He completed a degree in computer science last year, and is now doing a graduate business diploma. There was a strong tendency to search for meaning and a good eye for inconsistency; the misconceptions shown in electromagnetism are especially interesting for this reason. He commented that electromagnetism was the hardest part of the physics course for him.

There was a good qualitative grasp of the field concept, and of field lines. The electric field was seen as representing the amount of force that would be exerted on a charge placed at that point, and similarly for a gravitational field. There was difficulty relating this to quantitative equations, as a result of having forgotten the meaning of quantitative field strength at a point, E. Indeed, he spontaneously produced the equation $F = E\ q$ from the general question "what do you remember being taught about electromagnetism in school", but could not remember what E stood for. When prompted about vectors, he could relate the field strength at a point to the magnitude of a vector parallel to the field line.

His grasp of motors and generators was good on a systems level (brushes, magnets, coils of wire, rotation, induced currents), but his confusion about the right hand rule (discussed below) made it difficult for him to say exactly how the directions of motion and current flow were related.

The "right hand rule" and its different definitions were a source of confusion for subject C. He decided that the three quantities related were force, velocity and magnetic field. This caused some problems when he tried to apply the rule to problems involving forces due to currents. Searching for a consistent solution, he made the very reasonable suggestion that the current could be seen as a moving charge, and that meant that v would be parallel to the current. Less successful was his attempt to explain induction in a moving wire using this rule, where he decided that the charge in the wire would be moved to one side and so produce the F in his formulation of the right hand rule. He remembered the right hand "grip" rule clearly.

Subject C had unconventional ideas about the magnetic field. He was vague about why magnets affected iron filings and decided it was because iron filings were conductors. Consistent with this idea, he decided that the difference between magnetic and electric fields was that magnetic fields affected conductors and electric fields affected charged particles. He remembered that charged particles were affected by magnetic fields, and decided that this must be because "I seem to recall that all magnetic fields have an associated electric field at right angles to them". So the reasoning was that magnetic field itself does not affect the charged particle, but the eletric field which is always associated with it will.

The more abstract notions of flux and potential were not clear for subject C. He decided that potential was the same thing as field strength (note that this gives qualitatively reasonable results in the point-charge case). For flux, he recalled that "change-in-flux" meant something, but guessed that flux had something to do with how far the field spread, and that flux density had something to do with how much current could be drawn from a magnetic field.

Comments on pilot 2

Firstly, in terms of important new points about understanding of electromagnetic interactions: The two subjects with relatively elaborate knowledge structures (subjects A and C) both had trouble with the concepts relating to fields - the equations of field strength and their relation to other ideas, such as flux and potential. They were having difficulties also with the difference between electric and magnetic fields. Additionally, the consistent application of the right-hand rule in various situations was problematic for them. These are useful points for further study.

In terms of interview procedures, it seemed clear that interviews are not as sensitive to the exact wording of the question set as written tests, as the interviewer is in a position to clarify subjects' answers by further probing. The questions used seemed to give acceptable results in terms of revealing subjects' understandings in the area.

The case study of individual students proved to give a useful way of investigating their understandings, and showing how the various concepts fitted together in their minds. This approach was therefore marked for inclusion in the main study.

PILOT 3: YEAR 12 PHYSICS CLASS

This pilot study was especially useful in the light it threw on question development. Most of the questions did not receive answers which revealed a great deal about subjects' understandings of electric and magnetic fields.

Methodology of pilot 3

A Year 12 physics class in Queensland was available for a written test of 30 minutes duration in July 1993; this class was in the midst of a course on electricity and magnetism. The written test was administered in class time by the teacher to the nine students. The test used appears at the end of this appendix, with each question followed by a comment in italics about the purpose of that question - these comments were prepared before the test was given, and were not included in the test as administered to the students.

Results of pilot 3

Understandings of magnets

The question about lines in iron filings near a magnet did not elicit a wide range of responses. All students drew a reasonable pattern of lines, but none gave an explanation of why the pattern forms. It seems that a greater range of response would be elicited if one were to ask more sub-questions about the mechanism that makes the filings form this pattern, and providing a picture of the pattern rather than asking students to draw it; this insight applies to use of the question in the main study.

Understandings of fields

This section contained a number of questions simply asking students to explain what some term meant: electric field, electric field at a point, a field line, "E". The responses to these questions were not well distributed, with a preponderance of simple answers. It seemed that questions asking students to describe the meaning of technical terms about fields were not generally productive of interesting results and this was noted for the main survey.

It was difficult to draw conclusions about the effectiveness of the later questions in the test, because the majority of these students did not have time to do those later questions.

Comments on pilot 3

Overall, the students showed mastery as far as their level of response - that is, their answers were generally never wrong, though often rote or simplistic. It seems likely that the points they skimmed over - the mechanism that forms the pattern in the iron filings, the meaning of those lines in the pattern, the meaning of the electric field at some point in space - are probably not clear in their minds. The greatest outcome from this pilot was useful feedback on question format, and developing questions intended to force students to confront those points that were skimmed over in responses to pilot 3.

OUTCOMES OF PILOT STUDIES

A number of useful points emerged from the three pilot studies. The questions used were refined in the light of responses given. The existence of some postulated alternative conceptions was confirmed. Unfortunately, the amount of data collected was too sparse to conjecture at the underlying structure in terms of SOLO levels.

Some questions were found to give an inadequate range of answers, others were found to encourage simple answers. Each of the questions used in the pilot tests was examined in the light of the answers it received, and appropriate action was taken. Several written questions have benefited from their pilot trialling, which has helped improve their form. The question involving iron filings in the field of a magnet was refined twice, moving to make tautological answers less attractive. Certain questions were eliminated as not likely to produce useful written answers. This allowed for an improvement in the main data collection. There was also a general appraisal of the technique of interviewing, in terms of approaches which were effective in questioning students. The answers elicited by the questions revealed some preliminary data about students' understandings of concepts.

The subjects of the pilot tests had difficulty with the concepts describing fields. The concept of field lines, and the relationship of this concept to that of field strength at a point was problematic for them. Potential was not a clear concept in their minds, and the idea of flux was not well defined either. There was no clear distinction between electric and magnetic fields. The interview subjects had difficulty explaining movement of electric charges in magnetic fields, becoming confused about the nature of the right hand rule describing phenomena in these situations. These misconceptions were targeted in the main study.

The instruments used for the three pilot studies are given below, in order of use.

WRITTEN TEST FOR PILOT 1

The below test was given to the Year 11 physics class that formed the subjects for pilot 1. Each question in the test has been annotated below. The annotation, in italics, indicates the researcher's motivation for asking the question. The test is broken up into sections: Fields, vectors, proportional reasoning, magnets and circuit electricity. Each section also has a statement of motivation for interest in the area.

Fields:

The concept of a field is central to study of electro-magnetic phenomena. These questions are concerned with the students' understandings of some key concepts about fields.

1) If a charge of +2 coulombs experiences a force of 3 newtons at a point, what is the electric field strength at that point? Why? Will the force be in the direction of the electric field? Why?

1. Do they understand, or at least remember, that the magnitude of an electric field at a point is the force on a unit charge at that point? Do they understand or remember that the field direction at a point is defined as the direction of the force on a positive charge at that point? Understanding this test-charge definition of electric field can give a unifying structure for student's understandings of field phenomena.

2) What do you understand by (i) an "electric field"? (ii) a "field line"?

2) Another question probing their understanding of the concept of field. Field lines are quite an abstract concept and it will be interesting to see the interpretation placed on them by students.

3) There are two charges in this diagram, creating an electric field as shown. A small positive charge is placed at point X, will there be a force on it? Explain why. Will there be any difference if the charge is placed at point Y? Draw arrows at X and Y to show the direction of the force, if any.

3) This question is intended to see if students realise that force is always parallel to field lines. Also intended to see if students realise that the field lines fill all points in space, not just the lines drawn in the diagram. It is hypothesised that some students may predict a force on X, which is on one of the "field lines" drawn in the diagram, and not at Y, which doesn't.

4) Can you draw the equipotential lines (lines of equal potential) in (3)? Can you explain in detail what they mean?

4) Understanding of equipotential lines and surfaces is a basis for understanding the force field as the vector differential of the potential field

Vectors:

Understanding of vector addition and vector components is essential for understanding of relationships in electro-magnetic induction..

1) This diagram shows vectors **A** and **B.** Draw the vector **A** + **B**

1) Tests knowledge of vector addition - important in superposition of fields.

2) If vector **A** in the above diagram is 2 units long, what are the components of vector **A** perpendicular and parallel to vector **B**?
2) Tests ability to find components of one vector relative to another without a full co-ordinate system being given - in induction perpendicular components are important

Proportional Reasoning:
A rectangular box has a volume of 1.39 m^3. If the length and width are doubled and the height stays the same, what is the new volume? Explain why.
Mathematical relationships between quantities are central to physics. It has been found (Pegg, 19??), that surprising numbers of high school students have difficulty applying proportional reasoning about relationships in this box question. Note that this is a simple linear relationship - doubling length doubles volume. Pegg, and Collis, suggest that answering this question requires thought at the level of SOLO's formal mode. The formal SOLO mode may be of great importance to the study. Additionally, many formulae in the HSC electromagnetism syllabus have a linear form similar to Vol = lbh, eg e.m.f. = $lvB\sin(\phi)$, or $F=qvB\sin(\phi)$. If students have difficulties with the more familiar relationship between volume of a box and its sides, it is hard to expect them to fully understand the less familiar forms, yet alone non-linear relationships.

Magnets:
1) When two magnets are brought together, they may either attract or repel each other. Explain what is happening in each case, and why.
1) This question is intended to find out if students have a working knowledge of opposite poles in magnets.

2) Describe in as much detail as possible what you understand by a "magnetic field"? *2) The intent here is straightforward - to find their understandings of this term for comparison with scientists' understandings.*

3) What do you see as the similarities and differences between magnetic fields and electric fields? *3) The literature has shown that students frequently confuse electric and magnetic fields, and their effects on charges. This question is intended to find out if this is the case for these students.*

4) If you hold a magnet under a sheet of paper covered with iron filings, the iron filings form a pattern.

(i) What does this pattern look like?
(i) Intended to find out whether students were familiar with this phenomenon and the details of what is observed.

(ii) Explain why this pattern forms. Why does it look the way it does?
(ii) Do they have knowledge of the principles forming the pattern? Do they know the 'right' answer? Which alternative conceptions are common among students?

(iii) If you were to repeat the experiment (that is, start all over again with the same materials) would the pattern look the same? Why?
(iii) Do they realise that the iron filings will follow slightly different adjacent field lines next time?

(iv) What is the relationship between the pattern in the iron filings and the magnetic field of the magnet?
(iv) Similar to (ii). Forcing them to consider the magnetic field, if their explanation for (ii) did not include it.

Circuit Electricity:
The science education literature has suggested that even university physics students commonly have quite basic misconceptions about the nature of current and voltage. If students do not understand these, then what does this imply for their understanding of the voltages and currents involved in electromagnetic phenomena?

1) Explain in as much detail as you can what you understand by the terms "current", "voltage", and "electrical energy".
1) Another question with objectives exactly as stated - what do they understand about the terms?

2) What do the terms in question 1 have to do with each other?
2) Another question with objectives exactly as stated - the literature has shown that even quite advanced students frequently have confused ideas about these terms, and use them interchangably.

3) A brand-new torch battery is still in its package. Is there any current? Is there any voltage? Why?
3) Follows from suggestions in the literature that a common misconception is that a battery delivers a constant current, even when not connected - the literature has suggested that this is due to a model of electricity as essentially involving current, with voltage as a secondary and less used concept in students' minds.

4) (i) The circuit in diagram (a) has a bulb added, making the circuit in (b). What is the effect of this? Are the bulbs brighter in (a) or (b)? Discuss why.
(i) Do students tend to see the battery as a constant current source?

(ii) Another bulb is added, as shown in (c). Are all 3 bulbs in (c) the same brightness? Are they the same brightness as the single bulb in (a)? Discuss why.
(ii) Do students still reason with the battery as a constant current source - how do they relate this to energy considerations? Do they believe that changes in the circuit have no effect "upstream"?

INTERVIEW SCHEDULE FOR PILOT 2

This interview schedule guided the taped interviews with graduates of high-school physics in the second pilot study. It was arranged into three sets, based on students' spontaneous recellections, their knowledge of practical applications, and their knowledge of technical details, respectively:

Set 1: Probing the spontaneous recollections of students.
What do you think of when you hear the word "electromagnetism"?
Is it relevant to your life?
Can you think of any uses for it?
When did you learn about it? Did you feel you understood it well? Have you used it since?
What can you remember being taught about it in school?
When you were being taught about it in school, which parts seemed hardest to understand?
How do the applications you mentioned before relate to what you learnt about electromagnetism in school?
Can you see any sort of logical connection between the things you can remember about electromagnetism?

Set 2: Probing for knowledge about practical applications of electromagnetism
How does an electric motor work?
How does an electric generator work?
What does an electric transformer do? How does it work?
How does a [direction-finding] compass work?
What happens when you put iron filings on a piece of paper over a magnet? Why? How does that relate to the "magnetic field" of the magnet?

Set 3: Prompting for specific technical concepts
What is an "electric field"? A magnetic field? A gravitational field? A field?
Does a field have boundaries? Where?
What happens if I put a stationary electron in a magnetic field? In an electric field?
What if a charge is placed between electric field lines?
What is a "field line"? What is between the field lines in a drawing?
What is "flux"?
What is the effect if a wire is moving through an electric field? What things does this effect depend on?
What happens if a current is passed through a wire which is in a magnetic field? What things does this effect depend on?
What happens if a charge travels through a magnetic field?
What if the charge is moving parallel to the field?
What is the "right hand rule"? What does it mean? Give an example of its use.
Do you remember any other similar rules? Details?
Do you remember what a vector is? If so, how would vectors be used in electromagnetism?
How do vectors relate to electric fields? To the force on a moving charge in a magnetic field? To induction in a wire moving in a magnetic field?
Is a current or a voltage induced by electromagnetic induction? What *is* a voltage? What is an emf?
What is electric potential?
What does it mean to talk about a "potential difference"?

How does electric potential relate to the electric field? Field lines?
Does it seem to you that the facts you remember about electromagnetism fit together, or that they are just a collection of bits and pieces? What connections do you see between them?

WRITTEN TEST FOR PILOT 3

This written test had similarities to the written test of pilot 1, although a number of questions have been modified or discarded in the below test as a result of the students' answers in pilot 1. The text below is organised in the same way as was used for pilot 1 above: questions are arranged under topic headings, and there is a statement in italics following each question, explaining the objective behind asking that question.

Magnets:

1) If you hold a magnet under a sheet of paper covered with iron filings, the iron filings form a pattern.

(i) What does this pattern look like?
How familiar are they with the phenomenon? Do they know roughly what happens?

(ii) Explain why this pattern forms. Why does it look the way it does?
What are their ideas here? How do they explain the lines in the iron filings?

(iii) If you were to repeat the experiment (that is, start all over again with the same materials) would the pattern look the same? Why?
Do they have an eye for the constancy of the magnetic field? Do they realise that the lines in the iron filings ought to be slightly different the next time?

(iv) What is the relationship between the pattern in the iron filings and the magnetic field of the magnet?
Forcing them to consider this point if their answer to (ii) didn't include it.

(v) Explain why the iron filings don't just go straight to the poles of the magnet.
This is quite a deep question. I expect that their explanations will probably give the field lines too much reality.

Fields:

1) What do you understand by

(i) an "electric field"?
This seems likely to be 'an area of space affected by electric charge' or something along those lines. It will be more interesting in conjunction with (ii) and (iii)

(ii) the "electric field" at some point?
*The field at a point, **E**, being a vector ratio, seems to present conceptual troubles for students. Do they have a clear concept?*

(iii) a "field line"?
The exact definition of a field line is quite abstract. Do they have other, simpler ideas?

2) Explain what the symbol "E" in the equation "F = qE" stands for.
Do they have a clear concept to relate to this mathematical formalism?

3) A certain charge in an electric field experiences a force of 3.4 N. If the magnitude of the charge is doubled and the strength of the electric field is doubled, what happens to the force on the charge? Explain why.
Can they cope with this generalised ratio reasoning in this context? The idea of field at a point involves a ratio concept, E is the ratio of F q for any q.

4) There are two charges in this diagram, creating an electric field as shown. If a small positive charge is placed at point X, will there be a force on it? Explain why or why not. Will there be any difference if the charge is placed at point Y? Draw arrows at X and Y to show the direction of the force, if any.
Do they give too much reality to the field lines in their ideas? Do they predict that charges will be drawn to the field lines, or that those off them will feel no force?

5) If we know the potential at a point in a field, does this tell us the voltage? Does it tell us the field strength? Explain why or why not.
Field strength and potential are often confused by learners.

6) Explain the relationship between potential, voltage and field strength.
Ditto.

7) What do you see as the similarities and differences between magnetic fields and electric fields?
The literature states that these concepts are often completely synonymous in learners' minds.

Proportional Reasoning:
1) A rectangular box has a volume of 1.39 m^3. If the length is made three times as large, the width is doubled and the height stays the same, what is the new volume? Explain why.
Can they use proportional reasoning in this more familiar case even if not in the example above with electric fields?

Circuit Electricity:
1) A brand-new torch battery is still in its package. Is there any current? Is there any voltage? Explain why.
This question should reveal confusions about the relationship of voltage to current, as well as 'current centred' views of battery operation. These will probably carry on into understandings of electromagnetic interactions.

APPENDIX E

The physics course and its pre-requisites.

This appendix reproduces the relevant page from the 1993 University of New England Handbook, which describes the physics course from which students were taken for the main data collection of this thesis. The "desirable background" including high-school physics implies that students are expected to be encountering many of the concepts in the course for the second time.

Postgraduate Study

Candidates are accepted for the degrees of MLitt, MA, MSocSc and PhD in Philosophy. The research topic is settled by discussion with the Head of the Department. The Department offers a two-year MLitt Preliminary Course, designed for *graduates* who wish to proceed to a MLitt in Philosophy but who have not previously studied the subject.

Intending candidates for a higher degree should consult the Head of the Department before making formal application for admission.

Enquiry in Social Science

The Department offers the following Enquiry in Social Science units in Philosophy of Social Science. They are compulsory for BSocSc students, and available to BA students. These do not require Philosophy 100-2 as a prerequisite. See also the Schedule of the Faculty of Arts Rules.

Enquiry Soc Sc 223-1 Philosophy of Social Science A (1993, 1994)

A First Semester unit of two lectures and one tutorial per week. An introduction to philosophy of social science. Critical discussion of dogmatic, relativistic, and "liberal" attitudes to theoretical diversity in social science; the secular character of social theory; the assumption that there are "hidden" social realities; and the implications for human moral practices of a scientific approach to human social phenomena.

Prescribed Book

Richards, S., *Philosophy and Sociology of Science*. Blackwell.

Enquiry Soc Sc 224-1 Philosophy of Social Science B (1993, 1994)

A Second Semester unit of two lectures and one tutorial per week. Various topics in methodology of the social sciences. Motives and criteria for the success of the social explanatory enterprise; rational and causal modes of explanation; relations between individuals and institutions; techniques for the identification of individuals' reasons for action; and ethical problems associated with social scientific research.

Prescribed Book

Trigg, R., *Understanding Social Science*. Blackwell.

PHYSICS

First-year Units

Physics 101-2

Three lectures and one afternoon of practical work each week throughout the year. Regular tutorial assistance is available.

The desirable background for this unit is the equivalent of a NSW tertiary entrance ranking of more than 73 including physics and 3-unit mathematics. Students with a lower level of preparation are advised to enrol in Biophysics 111/112.

The unit meets the requirements of those students who wish to major in Physics, Geophysics, or Engineering, but is also suitable for students who wish to proceed in Mathematics, Computing Science, Chemistry, Resource Management or the Biological Sciences.

The material to be covered will include properties of matter, heat, mechanics, electricity and magnetism, waves, optics, semiconductors and elementary quantum physics.

Prescribed Books

First Year Laboratory Manual for Physics (available from Department).

Giancoli, D.C., *Physics for Scientists and Engineers with Modern Physics*. 2nd ed. Prentice-Hall.

Biophysics 111-1

This one-semester unit may only be credited in conjunction with Biophysics 112-1, to provide two credit points.

The material covered includes: a description of human and animal movement using the basic laws of mechanics, gravitation and elasticity; the acoustics of the ear and the optics of the eye; an analysis of neurons and neural systems using the basic concepts of electric charge, electric potential and resistance; the principles of the the electrocardiograph and the electroencephalograph.

The unit comprises three lectures and one afternoon of practical work each week throughout First Semester. Regular tutorial assistance is available.

Prescribed Books

First Year Laboratory Manual for Biophysics (available from Department).

Urone, P.P., *Physics with Health Science Applications*. Wiley.

Biophysics 112-1

This one-semester unit provides one credit point in the Schools of Rural Science and Natural Resources. In the School of Science it may only be credited in conjunction with Biophysics 111-1, to provide two credit points.

The material covered includes: Fluid statics and dynamics applied to flotation, capillaries, soils, sedimentation, diffusion, osmosis, blood flow, water rise in trees and breathing; the electromagnetic spectrum, spectroscopy, luminescence, scattering of light, polarised light, lasers, X-rays, radioactivity and the biological effects of radiation; heat flow, energy use and temperature regulation in plants, animals, ecosystems and the atmosphere.

The unit comprises three lectures and one afternoon of practical work each week throughout Second Semester. Regular tutorial assistance is available.

Prescribed Books

As for Biophysics 111-1.

Second Year Units

The following second year units are available:

Physics 201-1 Quantum Mechanics, Thermodynamics, Nuclear Physics

Physics 203-1 Relativity, Electromagnetism

APPENDIX F

Outline of the course in electricity and magnetism.

This appendix reproduces the advance organiser which the lecturer gave to the tertiary students of the main study at the commencement of their course in electricity and magnetism. This illustrates the scope and sequencing of the course.

Physics 101-2

ELECTRICITY AND MAGNETISM

Textbook: D.C. Giancoli, 'Physics for Scientists and Engineers with Modern Physics', 2nd Ed., Prentice-Hall

Relevant sections of the text are referred to by number in each part of the syllabus below.

Syllabus

1. Electrostatics (Chapter 23 and 25)

   Electric charge and Coulomb's law.
   Electric field and its calculation for charge distributions, lines of force.
   Electric potential and potential difference, equipotential surfaces, relation between electric potential and electric field.
   Electron motion in the cathode-ray oscilloscope, the electron volt.
   Electric potential and potential energy for charge distributions.
   Electrical breakdown of air.

2. Current and dc circuits (Chapters 27 and 28)

   Electron drift in a conductor.
   Ohm's law, resistance, resistivity, superconductivity.
   Energy and Power, the kilowatt hour.
   Emf, terminal voltage, internal resistance.
   Resistors in series and parallel.
   Kirchhoff's rules and application, potential divider.
   Emfs in series and parallel.
   Voltage and current sources

3. Magnetism (Chapters 29 and 31-1 to 31-5)

   Magnetic field, magnetic force on a current-carrying wire and on a moving charge.
   Circular motion in uniform magnetic field, mass spectrometer.
   Torque on a current loop, galvanometer, electric motor.
   Electromagnetic induction, magnetic flux, Faraday's law, Lenz's law, electric generator.

4. Alternating Current (Chapter 32, 26-1 to 26-5, 33-1 to 33-6)

   Alternating currents and voltages, rms values.
   Mutual and self inductance, transformers.
   Capacitance, capacitors in series and parallel, RC circuit.
   Resistive, capacitive and inductive ac circuits, reactance.
   LRC circuit, impedance, phase angle, resonance.

G.A.W./B.M.S.: 1993

APPENDIX G

Extract from the New South Wales Higher School Certificate syllabus (1979) for 2-Unit Physics.

The 2-Unit physics course was regarded as background for the university physics course which supplied students for this thesis. Comparison of the content described here with that described in the university course outline of appendix F shows considerable overlap, implying that the students are indeed encountering many of these concept for the second time.

d) **ELECTRICAL INTERACTIONS**

A study of electric currents, their relation to motion of charge and the magnetic effects of a current.

A student should -

* *develop a concept of electrical charge as something which bodies may acquire, lose or transfer and which gives rise to forces between them*

* *gain an understanding of the interaction between charged objects and develop the concept of an electric field as a means of expressing the strength and direction of this interaction, using mathematical models (inverse square law) to analyse the interaction.*

* *be aware of the changes in energy which occur as charges move in electric fields and hence develop an understanding of potential and potential difference.*

* *develop an accurate concept of electric current and resistance in terms of the motion of electric charge, and the relation of potential difference to the energy available in a circuit*

* *gain practical experience with reading circuit diagrams, wiring circuits and using electrical meters*

* *be able to analyse d.c. circuits quantitatively including the application of Ohm's Law to situations of simple series, parallel and series/parallel networks, with calculations of current, voltage, resistance, energy and power*

* *develop an understanding of the magnetic fields associated with permanent magnets, straight conductors and coils*

* *understand the concepts of 'flux' and 'flux density' in both verbal and numerical terms*

Suggested Experiences

* *design/build/use some electrostatic machines*

* *use the electroscope in investigate charge*

* *map the electric fields between electrodes of various shapes using conducting paper or liquids*

* *investigate the inverse square law*

* *use circuit boards to investigate the behaviour of series and parallel circuits*

* predict and measure voltages and currents in resistance networks

* measure the voltage drop along a uniform wire

* examine quantitatively the heating effect of an electric current

* plot and predict magnetic fields in various situations

e. *ELECTROMAGNETISM*

A study of electromagnetic phenomena and some of the mathematical models which have been developed to understand and use them. A sound practical experience of the effects should be the basis of the unit, nevertheless the student requires a considerable degree of formal thinking ability to handle the unit successfully.

* *motor effect*
  - o *direction and magnitude of forces on charges moving in a uniform magnetic field*
  - o *force on a current-carrying conductor in a uniform magnetic field (N)*
  - o *force between two current-carrying conductors; definition of the ampere (N)*
  - o *torque on a rectangular coil in a uniform magnetic field (N)*
  - o *application of the effect to simple d.c. motors and meters (D,E)*

* *electromagnetic induction*
  - o *induced e.m.f. for a conductor moving across a magnetic field, back e.m.f. in motors (D,N,E,)*
  - o *an understanding of induced currents in terms of the flux changes within the circuit; Faraday's and Lenz's laws (D,N)*
  - o *self-induction (D,E)*
  - o *applications, including generators, transformers and induction motors (D)*

Suggested Experiences

* *experiments which directly measure magnetic forces at points within a field*
* *experiments involving the deflection of cathode ray beams*
* *current balance experiments*
* *replication of Oersted's and Faraday's electromagnetic experiments*
* *construct and/or study some electromagnetic devices such as solenoids, relays, motors, generators and transformers*

APPENDIX H

Course test on electricity and magnetism

This test was given by the physics department to its students at the end of the part of their course which dealt with electricity and magnetism. Students' answers to this test are discussed in detail in chapter 4 of this thesis.

PHYSICS 101-2

2ND SEMESTER TEST

Thursday 16th September, 1993, 9.10 - 9.50 a.m.

The test will last for 40 minutes, will be marked out of 40 and marks for individual questions are given in brackets.

A sheet of formulae and fundamental constants is attached.

1. Define the *dielectric constant* of a material. (2)

2. A pair of parallel plates, separated by a distance d, has a potential difference V between them. Show that the electric field between the plates is V/d. (2)

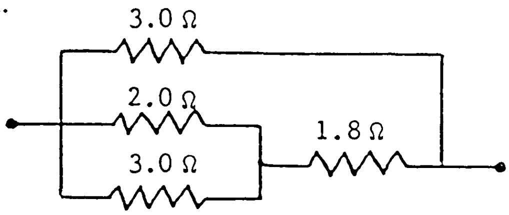
3. Why is the direction of an electric field at the surface of a charged conductor always normal to the surface? (2)

4. What is St. Elmo's Fire? (2)

5. Atmospheric air breaks down when an electric field greater than 3×10^4 V cm^{-1} is present. Calculate the potential on a conducting sphere of diameter 1 mm when the air around the sphere breaks down. (2)

6. An electron is released from rest in a uniform electric field of 1000 N C^{-1}. After it has moved through 2 m, calculate the electron's (i) kinetic energy in electron volts, (ii) velocity. (3)

7. (a) Derive an expression for the effective resistance of a number of resistances connected in parallel. (3)
   (b) Calculate the effective resistance of the combination exhibited in the diagram. (4)



8. Using an appropriate diagram, explain the principle of a potential divider. (4)

9. (a) Write down a vector relationship for the force acting on a charged particle q moving with velocity v in a magnetic field B. (1)
   (b) Explain why it is not possible to change the speed of a charged particle by any combination of steady magnetic fields. (2)

10. At what frequency does a 2.0 mH inductance have an inductive reactance of 2 kΩ? (2)

11. A series RC circuit consists of a resistance of 30 Ω and a $25/\pi$ μF capacitor in series with a 240 V rms ac source operating at 500 Hz.
   (a) Calculate the rms current in the circuit. (4)
   (b) Calculate the rms voltage drop across each of R and C. (4)
   (c) Sketch a phasor diagram for this circuit and indicate on it the phase angle between the voltage source and the current in the circuit. (3)

LIST OF EQUATIONS

$\mathbf{F} = \frac{k_E Q_1 Q_2}{r^2}\hat{\mathbf{r}}$ $\quad k_E = \frac{1}{4\pi\varepsilon_o}$ $\quad \mathbf{E} = \mathbf{F}/q$

$Q = Q_0\left(1 - e^{-t/RC}\right)$ $\quad V = IR$ $\quad I = Aqnv$

$I = dQ/dt$ $\quad R = R_1 + R_2 + R_3 + ...$ $\quad R = \rho\ell/A$

$P = IV$ $\quad \mathbf{F} = I\underline{\ell}\times\mathbf{B}$ $\quad \frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + ...$

$\mathbf{F} = q\mathbf{v}\times\mathbf{B}$ $\quad \Phi = \int \mathbf{B}\cdot d\mathbf{A}$ $\quad \mathbf{F} = q(\mathbf{E} + \mathbf{v}\times\mathbf{B})$

$\tau = NI\mathbf{A}\times\mathbf{B}$ $\quad C = Q/V$ $\quad \varepsilon = NBA\omega\sin\omega t$

$\varepsilon = -N\frac{d\Phi}{dt}$ $\quad \varepsilon = -L\frac{dI}{dt}$ $\quad Z = \left\{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2\right\}^{1/2}$

$v = f\lambda$ $\quad y = A\sin(kx - \omega t)$ $\quad f' = f\left(\frac{v \pm v_o}{v \mp v_s}\right)$

$\beta = 10\log I/I_0$ $\quad v = \sqrt{T/\mu}$ $\quad v = \sqrt{B/\rho}$

$m\lambda = d\sin\theta$

$n_1\sin\theta_1 = n_2\sin\theta_2$ $\quad \frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$ $\quad \frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$

$\sin A + \sin B = 2\sin\frac{1}{2}(A+B)\cos\frac{1}{2}(A-B)$

$\cos A + \cos B = 2\cos\frac{1}{2}(A+B)\cos\frac{1}{2}(A-B)$

$\mathcal{R}(\lambda) = \frac{2\pi c^2 h}{\lambda^5}\left[\exp\left(\frac{hc}{\lambda kT}\right) - 1\right]^{-1}$ $\quad E = hf$

$\mathcal{I} = \sigma T^4$ $\quad E_n = -\frac{me^4}{8\varepsilon_o^2 h^2 n^2}$ $\quad p = h/\lambda$

$\frac{1}{2}mv_{max}^2 = hf - W_o$ $\quad \lambda_{max}T = 2.9\times10^{-3}\,\text{m K}$

$N(t) = N(0)\,e^{-\lambda t}$

Fundamental Constants

Permittivity of free space
$\varepsilon_0 = 8.85 \times 10^{-12}$ $C^2 N^{-1} m^{-2}$

Electrostatic Constant
$k_E = \frac{1}{4\pi\varepsilon_0} = 9 \times 10^9$ N m^2 C^{-2}

Avogadro's number
$N_A = 6.02 \times 10^{23}$ mol^{-1}

Speed of light in vacuum
$c = 3.0 \times 10^8$ m s^{-1}

Stefan-Boltzmann constant
$\sigma = 5.7 \times 10^{-8}$ W m^{-2} K^{-4}

Boltzmann's constant
$k = 1.4 \times 10^{-23}$ J K^{-1}

Planck's constant
$h = 6.6 \times 10^{-34}$ J s

Electron rest mass
$m_e = 9.1 \times 10^{-31}$ kg

Magnitude of electronic charge
$e = 1.6 \times 10^{-19}$ C

mass of proton = 1.00728 u

mass of neutron = 1.00867 u

mass of electron = 0.00055 u

1 u = 1.660×10^{-27} kg

APPENDIX I

End-of-year course test in physics

This test was given by the physics department at the end of the year, and includes a section on electricity and magnetism as well as others on different topics. Students' answers to the relevant questions in this test are discussed in detail in chapter 4 of this thesis.

THE UNIVERSITY OF NEW ENGLAND

UNIT NAME: PHYSICS 101-2

PAPER NUMBER: SECOND PAPER

PAPER TITLE: ELECTRICITY AND MAGNETISM, WAVES AND OPTICS and ATOMIC AND NUCLEAR PHYSICS.

DATE: Thursday 11th November, 1993 TIME: 2.00 p.m. to 5.00 p.m.

TIME ALLOWED: THREE HOURS plus reading time of FIFTEEN MINUTES

NUMBER OF PAGES IN PAPER: EIGHT (8)

NUMBER OF QUESTIONS ON PAPER: NINE (9)

NUMBER OF QUESTIONS TO BE ANSWERED: SIX questions including at least TWO from each Section.

STATIONERY PER CANDIDATE: [1] X 6 LEAF A4 BOOKS [1] X 12 LEAF A4 BOOKS

[-] X ROUGH WORK BOOKS

GRAPH PAPER: NIL (NUMBER OF SHEETS)

POCKET CALCULATORS PERMITTED: YES~~XXX~~ (SILENT TYPE)

MATHEMATICAL TABLES PERMITTED: ~~XES~~ NO; ~~XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX~~

OTHER AIDS REQUIRED: NIL

INSTRUCTIONS FOR CANDIDATES: Lists of equations and fundamental constants are attached. Each question is worth 20 marks. Marks for parts of Questions are shown in parenthesis in the right-hand margin. Candidates may make notes on this paper during the reading time.

Candidates may retain their copy of this examination question paper.

TEXTBOOKS OR NOTES PERMITTED: NIL

THE UNIVERSITY CONSIDERS IMPROPER CONDUCT IN EXAMINATIONS TO BE A SERIOUS OFFENCE. PENALTIES FOR CHEATING ARE EXCLUSION FROM THE UNIVERSITY FOR ONE YEAR AND WITHDRAWAL WITH FAILURE FROM THE COURSE CONCERNED.

93/302/1

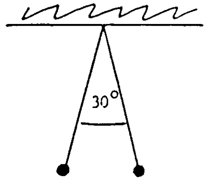
SECTION A

Question 1

(a) Sketch graphs to show how the electric field and electric potential depend on the radial distance from the centre of a charged conducting sphere, both inside and outside the sphere. (3)

(b) Define the *dielectric constant* of a material. (2)

(c) Two spheres of equal size and mass are suspended from the same point by fine insulating threads of length 1.0 m. When each sphere carries a positive charge of 1.5 μC, the angle between the threads is 30° as shown in the figure below.



(i) Sketch a diagram showing all forces acting on one of the spheres.
(ii) Calculate the mass of the sphere. (6)

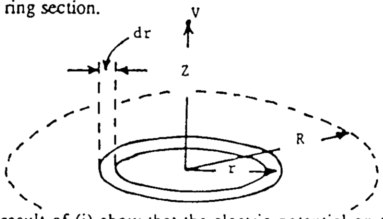
(d) A pair of parallel conducting plates, separated by a distance of 5.0 cm, have a potential difference of 1.0 kV between them. The plates are horizontal and the upper one is at the higher potential. A particle of mass 1.5 g carrying a charge of 2.0 μC is released from rest at the lower plate.

(i) Calculate the velocity of the particle when it reaches the upper plate. (5)
(ii) Calculate the potential difference between the plates for which the particle may be suspended in the region between the plates. (4)

Question 2

(a) A thin circular disc of radius R carries a uniform distribution of charge with a charge density of σ C m^{-2}.

(i) Consider a ring section of the disc of width dr at radius r as shown in the diagram. Write down the potential V due to the charge distribution on the ring section at a point a distance Z from the centre of the ring and on the axis of the ring section.



(3)

(ii) Using the result of (i) show that the electric potential on the axis of the disc, at a distance Z from the plane of the disc, is given by

$$V = \frac{\sigma}{2\varepsilon_0}\left[\left(R^2 + Z^2\right)^{1/2} - Z\right]$$ (3)

Question 2 continued on page 3.

Question 2 continued.

(iii) The disc has a diameter of 1.0 m and has 10^{10} electrons uniformly distributed over its surface. Calculate the electric potential at the centre of the disc. (4)

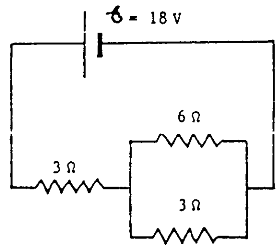
(b) Describe the function of a dc potential divider and derive an expression for the output potential difference available from the divider. (3)

(c) A 12-V car battery is used to run two 6-V 18-W light bulbs and a 9-V 0.03-kW motor.

(i) Draw a diagram of a circuit which allows all three components to be operated simultaneously, each at its rated voltage. A resistor must be added to the circuit. (4)
(ii) Calculate the value of the added resistor. (3)

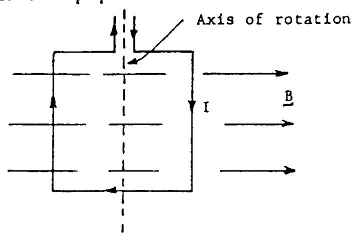
Question 3

A dc circuit consists of 3 resistors and a source of emf arranged as shown below.



(a) (i) Calculate the equivalent resistance of the three resistors. (3)
(ii) If the source of emf has an internal resistance of 1 Ω, calculate the current through it. (2)
(iii) Calculate the current in the 6 Ω resistor. (3)
(iv) Redraw the diagram including an ammeter to measure the total current in the circuit and a voltmeter to measure the voltage difference across the 6 Ω resistor. (2)
(v) State electrical characteristics required of both meters to ensure accurate measurements. (2)

(b) A square coil of one turn of wire and side ℓ is suspended in a uniform magnetic field **B** with the plane of the coil parallel to **B** as shown in the diagram. The coil is free to turn about an axis perpendicular to **B**.



Question 3 continued on page 4.

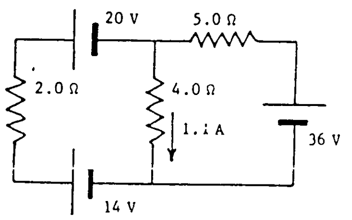
Question 3 continued.

At the instant that a current I commences to flow in the coil,

(i) determine the magnitude of the force and its direction acting on each side of the coil. (5)
(ii) Hence determine the torque on the coil at that instant. (3)

Question 4

(a) (i) Explain the physical basis of Kirchhoff's second or loop rule. (3)
(ii) In the circuit shown, calculate the currents in the 2.0 Ω and 5.0 Ω resistors. The sources of emf have negligible internal resistance. (7)



(b) (i) Explain what is meant by the *rms value* of an ac and relate that value to an equivalent dc. (3)
(ii) (A) Using phasor diagram notation, establish an expression for the ac impedance of a series LRC circuit.
(B) Show that resonance in this circuit occurs when the angular frequency ω of an applied emf is given by $\omega = 1/\sqrt{LC}$. (7)

SECTION B

Question 5

(a) Distinguish between longitudinal and transverse waves. (2)

(b) A transverse cosine wave travelling in the negative x-direction has an amplitude of 0.30 m, a wavelength of 2.0 m and a velocity of 6.0 m s^{-1}.
(i) Calculate the frequency and period of the wave.
(ii) Write down the equation of the wave.
(iii) Calculate the maximum transverse speed of a point on the wave. (7)

(c) (i) Explain in physical terms why the frequency of sound heard by a listener moving directly towards a stationary source is not the same as the frequency of the source.
(ii) Show in a sketch what happens to the wavefronts of the sound when the source is moving through the air. (6)

(d) An aeroplane producing a noise power of 8 W is flying at a height of 2 km. If the noise is transmitted equally in all directions, calculate the sound intensity level (dB) at the ground.

(0 dB is equivalent to 10^{-12} W m^{-2}) (5)

Question 6

An object of height 2.0 mm is positioned 3.0 cm in front of a thin converging lens of focal length 2.5 cm.

(a) Calculate the distance of the image from the lens. (3)

(b) Calculate the height of the image. (2)

(c) An eyepiece lens having a focal length of 4.0 cm is placed 18.5 cm from the first lens in order to form a microscope. Determine the position of the new image. (4)

(d) Draw a ray diagram to show the passage of the rays through the two lenses. (3)

(e) Calculate the angular magnification of the eyepiece assuming the eye has a near point of 25 cm. Derive any result that you may use. (6)

(f) Calculate the total magnification of the microscope. (2)

Question 7

(a) Two waves of slightly different frequencies f_1 and f_2 have the same amplitude. Show that when they overlap, the resultant wave can be viewed as a wave of frequency $(f_1 + f_2)/2$ with a slowly varying amplitude of $(f_1 - f_2)/2$. (5)

(b) Light of wavelength 600 nm is incident normally on a diffraction grating having 800 lines per mm. Calculate the angles of the light beams emerging from the grating. (5)

(c) (i) Explain the difference between a *p-type semiconductor* and an *n-type semiconductor.* (3)
(ii) Explain how a p-n junction diode acts as a *rectifier.* (3)
(iii) Draw a diagram for a full-wave rectifier circuit with smoothing and briefly explain its operation. (4)

Question 8

(a) (i) The *photoelectric effect* can be explained using a photon theory of light, but not a wave theory. Discuss. (5)
(ii) Sunlight reaching the earth has an intensity of 1300 W m^{-2}. Taking the average wavelength of sunlight to be 550 nm, calculate the number of photons striking the earth per square metre per second. (4)

(b) In 1885, Balmer showed that the wavelengths λ of the four visible lines in the hydrogen spectrum fit the relation

$$\frac{1}{\lambda} = R\left(\frac{1}{2^2} - \frac{1}{n^2}\right)$$

n = 3, 4, 5 or 6 and R is a constant = 1.097×10^7 m^{-1}.

(i) Explain how Bohr's model of the atom accounts for the form of Balmer's relation. (5)
(ii) Sketch an energy-level diagram for the hydrogen atom, showing the origin of the four spectral lines described by Balmer's relation. (3)
(iii) Use the Bohr model to account for the difference between an *emission spectrum* and an *absorption spectrum.* (3)

Question 9

(a) Radioactive decay may be described mathematically by the relation

$$N = N_0 e^{-\lambda t}$$

(i) Define each of the terms in this relation. (3)

(ii) Define the *activity* of a radioactive sample, and obtain an expression for it in terms of λ, N_0 and t. (3)

(iii) Define the *half-life* $T_{1/2}$ of a radioactive isotope and obtain an expression for $T_{1/2}$ in terms of λ. (3)

(iv) An ancient club is discovered which contains 180 g of carbon, and has an activity of $6\ s^{-1}$. Determine the age of the club using the fact that in living trees the ratio $^{14}C/^{12}C$ is 1.3×10^{-12}.
Decay rate λ of $^{14}C = 3.8 \times 10^{-12}\ s^{-1}$. (5)

(b) (i) Sketch a typical continuous X-ray spectrum and explain why the spectrum has a minimum wavelength. (3)

(ii) Calculate the shortest wavelength X-ray photon emitted by an X-ray tube operating at 60 kV. (3)

LIST OF EQUATIONS

$\mathbf{F} = \frac{k_E Q_1 Q_2}{r^2}\hat{\mathbf{r}}$	$k_E = \frac{1}{4\pi\varepsilon_o}$	$\mathbf{E} = \mathbf{F}/q$
$Q = Q_0\left(1 - e^{-t/RC}\right)$	$V = IR$	$I = Aqnv$
$I = dQ/dt$	$R = R_1 + R_2 + R_3 + \ldots$	$R = \rho\ell/A$
$P = IV$	$\mathbf{F} = I\underline{\ell} \times \mathbf{B}$	$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots$
$\mathbf{F} = q\mathbf{v} \times \mathbf{B}$	$\Phi = \int \mathbf{B} \cdot d\mathbf{A}$	$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$
$\tau = NIA \times \mathbf{B}$	$C = Q/V$	$\varepsilon = NBA\omega \sin \omega t$
$\varepsilon = -N\frac{d\Phi}{dt}$	$\varepsilon = -L\frac{dI}{dt}$	$Z = \left\{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2\right\}^{1/2}$
$v = f\lambda$	$y = A \sin(kx - \omega t)$	$f' = f\left(\frac{v \pm v_o}{v \mp v_s}\right)$
$\beta = 10 \log I/I_0$	$v = \sqrt{T/\mu}$	$v = \sqrt{B/\rho}$
$m\lambda = d \sin\theta$		
$n_1 \sin\theta_1 = n_2 \sin\theta_2$	$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$	$\frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$

$$\sin A + \sin B = 2 \sin\tfrac{1}{2}(A+B) \cos\tfrac{1}{2}(A-B)$$

$$\cos A + \cos B = 2 \cos\tfrac{1}{2}(A+B) \cos\tfrac{1}{2}(A-B)$$

$\mathcal{R}(\lambda) = \frac{2\pi c^2 h}{\lambda^5}\left[\exp\left(\frac{hc}{\lambda kT}\right) - 1\right]^{-1}$	$E = hf$	
$\mathcal{I} = \sigma T^4$	$E_n = -\frac{me^4}{8\varepsilon_o^2 h^2 n^2}$	$p = h/\lambda$
$\frac{1}{2}mv_{max}^2 = hf - W_o$		$\lambda_{max}T = 2.9 \times 10^{-3}$ m K
		$N(t) = N(0)\, e^{-\lambda t}$

Fundamental Constants

Permittivity of free space
$\varepsilon_o = 8.85 \times 10^{-12}\ C^2\ N^{-1}\ m^{-2}$

Electrostatic Constant
$k_E = \frac{1}{4\pi\varepsilon_o} = 9 \times 10^9\ N\ m^2\ C^{-2}$

Avogadro's number
$N_A = 6.02 \times 10^{23}\ mol^{-1}$

Speed of light in vacuum
$c = 3.0 \times 10^8\ m\ s^{-1}$

Stefan-Boltzmann constant
$\sigma = 5.7 \times 10^{-8}\ W\ m^{-2}\ K^{-4}$

Boltzmann's constant
$k = 1.4 \times 10^{-23}\ J\ K^{-1}$

Planck's constant
$h = 6.6 \times 10^{-34}\ J\ s$

Electron rest mass
$m_e = 9.1 \times 10^{-31}\ kg$

Magnitude of electronic charge
$e = 1.6 \times 10^{-19}\ C$

mass of proton = 1.00728 u

mass of neutron = 1.00867 u

mass of electron = 0.00055 u

$1\ u = 1.660 \times 10^{-27}\ kg$

APPENDIX J

Student results on course tests

This appendix briefly describes the students' responses to the course tests given in appendices H and I.

RESULTS FOR THE ASSESSMENT TESTS

The test papers for the year have been reproduced in appendices H and I, along with the equation sheet which accompanied both tests. All the students' answer scripts for these two tests have been analysed by the author. Not all test questions were relevant to this thesis's focus area of field-related phenomena. Only relevant questions from the tests have been considered in this chapter.

MID-SEMESTER TEST ON ELECTRICITY AND MAGNETISM.

This test (question paper and equation sheets in appendix H) was given in a normal lecture time and was of duration 40 minutes. It was intended to cover the topic of electricity and magnetism. Fifty-one students completed the test, with an average score of 39.2%. A table of student scores on each question is included below. Questions 7, 8, 10 and 11 dealt with circuit electricity and do not concern us here.

Scores by question for end of semester test

Question	Marks allocated	Average score
1	2	0.37
2	2	0.29
3	2	0.49
4	2	1.34
5	2	0.51
6	3	1.64
7	7	5.17
8	4	0.53
9	3	1.14
10	2	1.02
11	11	3.18
Total	40	15.67

The lowness of these average scores indicates the problems that students were having with the area. As the detailed analysis of responses in the main body of this thesis shows, students had even more conceptual difficulties than these scores would suggest, as most of their marks were obtained on conceptually simple questions.

YEAR-END TEST

55 students sat this examination, which covered the semester's work, and was in 3 sections. Average score for this test was 47.7%. Section A dealt with electricity and magnetism, the same area as the mid-semester test discussed above. The other sections were of no interest

to this study. As students were able to choose which questions to answer and which to leave, the number of responses to questions varied considerably more than the mid-semester test where students were expected to answer every question.

In this test a number of unrelated questions were grouped together to make a single question. It is impossible to judge which part of the question caused students to decide not to attempt it - for example, whether students who avoided question 1 of this test did so because they felt uncomfortable with the fields surrounding a charged sphere (part a), the definition of dielectric constant (part b), a problem in mechanics involving charged spheres on strings (part c), or behaviour of a charged particle in a horizontal capacitor (part d). It has to be assumed that students are attempting questions that seemed easiest to them. Hence, it was judged not useful to tabulate the scores for each question. However, the number of students attempting each question involving fields was noted. Also, the number of students attempting each sub-question was noted. The below table shows the number of students attempting each of the relevant sub-questions from the year end test.

Numbers attempting relevant questions on end of year exam

Question	number attempting
1 (any part)	46
1(a)	*38*
1(b)	*35*
1(c)	*46*
1(d)(i)	*40*
1(d)(ii)	*32*
2 (any part)	7
2(a)	*6*
3 (any part)	53
3(b)	*51*

Only 6 students attempted question 2(a). This is probably because it involves a rather complicated integration in three dimensions, and would appear to be of formidable difficulty for students with little experience in integrals of this sort.

The data from the tests is examined in detail in chapter 4, where it has been organised to bring out the themes of responses to quantitative questions and qualitative questions respectively. That chapter does not treat the questions in the same sequence as they appeared in the tests, which has allowed a logical structuring of each its sections.

APPENDIX K

Written test

This is the written test which was designed by the author of this thesis and administered to the subjects. It was followed up by an interview clarifying their written answers.

Name:

August 1993

This questionnaire is part of an investigation into students' understandings of field-related concepts in electricity and magnetism.

This is not part of the assessment for your physics course. However, it does represent a unique opportunity to explore the depth of your own understanding, and will help to guide your revision of the topic.

Your answer papers will be returned to you with written comments to aid your revision.

The results of this test will be used in research publications, but the anonymity of your answers will be respected.

Thank you for taking part in this study.

Signed

John Guth

John Guth
PhD Student, UNE

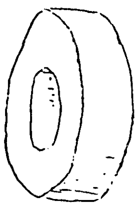
1) If you hold a magnet under a sheet of paper covered with iron filings, the iron filings form a pattern as shown.

(i) Explain why this pattern forms. We know large pieces of iron would go to the magnet. Why do the iron filings show the magnetic field of the magnet instead of simply going to the magnet?

(ii) What will happen if an iron filing is dropped into an empty space in the pattern? Why?

(iii) The pattern is now swept away, leaving the magnet by itself. What will happen if an iron filing is dropped where there used to be an empty space in the pattern? Explain why.

2) This is a round magnet. What might its magnetic field look like? Sketch all possible magnetic fields and explain why they are possible.



3) (i) Can you represent the electric field of these two point charges? Draw field lines. (see picture).

(ii) On the above diagram, indicate clearly any points where the field strength will be

(a) a minimum - explain why.

(b) a maximum - explain why.

(iii) On the above diagram, indicate clearly any points where the potential will be

(a) a minimum - explain why.

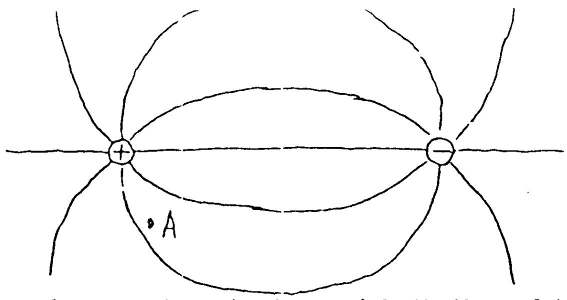
(b) a maximum - explain why.

4 (i) In the diagram above, 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?



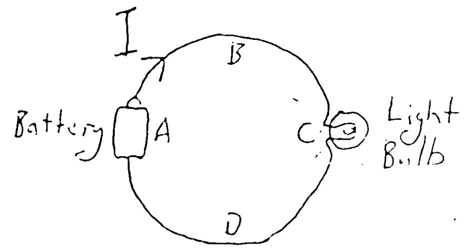
5) In the diagram above, the circles with "+" and "-" signs are positive and negative point charges. Indicate on the diagram the path a small positive charge will follow if it is released at point A. Could the mass of the charge make a difference? (yes/no). Explain why or why not.

6) In each of the capacitors above, an electron is placed at point A. The electric field then accelerates the electron until it hits point B. Compare the speeds of the electrons when they hit point B in capacitor 1 and capacitor 2. Explain the reasons for your answer.

7) Explain what 'flux' is in a magnetic field.

8) Given a cube with sides 1m long in a uniform magnetic field of 1 T, what is the total flux out of the cube?

9) Would you expect any difference in the strength of the magnetic field caused by the current at points A, B, C and D in this circuit (see diagram below)? Explain exactly what you would expect, and why.



10) A student drew the diagram below and suggested that a battery should always have a magnetic field around it when it wasn't in a circuit. Comment on this idea.

APPENDIX L

Interview protocol

This interview protocol is explained in chapter 3 under interview methodology. It applied particularly to the questions of clarification about students' written answers to the written test of appendix K.

NEO-NEWMAN INTERVIEW SCHEDULE

1) Reading
[unnecessary here]

2) Comprehension, interpretation
"in your own words, what is the question asking?"
"what does '....' mean?"

3) Strategy and skill selection
"Have you answered a question like this before?"
"What things have you learnt in your course that are relevant to this problem?"

4) Process
"How were you thinking as you wrote this?"
"Could you explain what you meant here?"
"Why is that true?"

5) Memory
"Did you consider how this aspect in your answer fits in with this other aspect?"
(point out inconsistencies)

6) Encoding
[irrelevant for these qualitative answers]

7) Consolidation
"What does the word '....' in your answer mean?"
"How about this piece of data in the question stem?"

8) Verification
"How sure are you of your answer?"
"How do you know this part is true?"

9) Conflict
"What if..." (some aspect of the situation changed)
"What if you saw something happening that was the opposite of what you've predicted - could you explain it?"

10) Similarity
"Is this problem similar to..." (some other problem). "Why/why not?"
"Could you write a similar problem?"
"Have you ever done a similar problem?"

11) Generalisation
"What overall principles did you apply here?"
"Could you imagine another situation where the same principles apply?"

APPENDIX M

Schedule for interview 2.

QUESTIONS FOR INTERVIEW 2

1) Can you use vectors to represent electric fields? Explain how they are used.

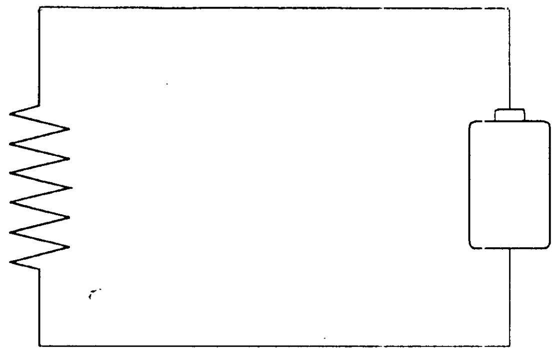
2) Can you use vectors to predict the interaction of two charges [pictured below]? Do so.

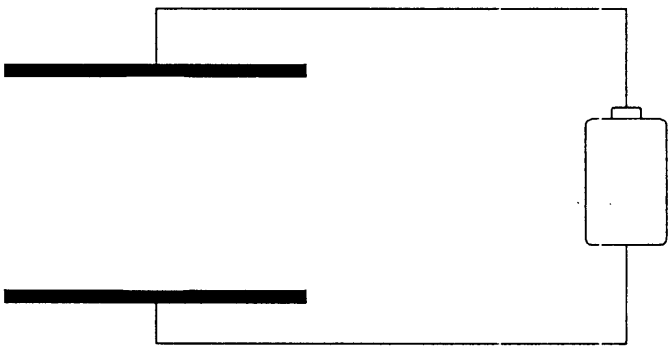
3) What <u>is</u> a vector?

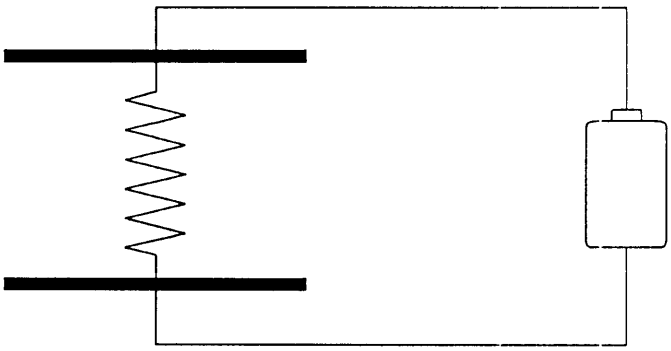
4) There is a current moving through a resistor [see figure below, top diagram]. Draw the field near the resistor. How do you know that field is correct? Explain what the lines you drew mean.

5) There is a capacitor charged by a battery [see figure below, middle diagram]. Draw the field in the capacitor.

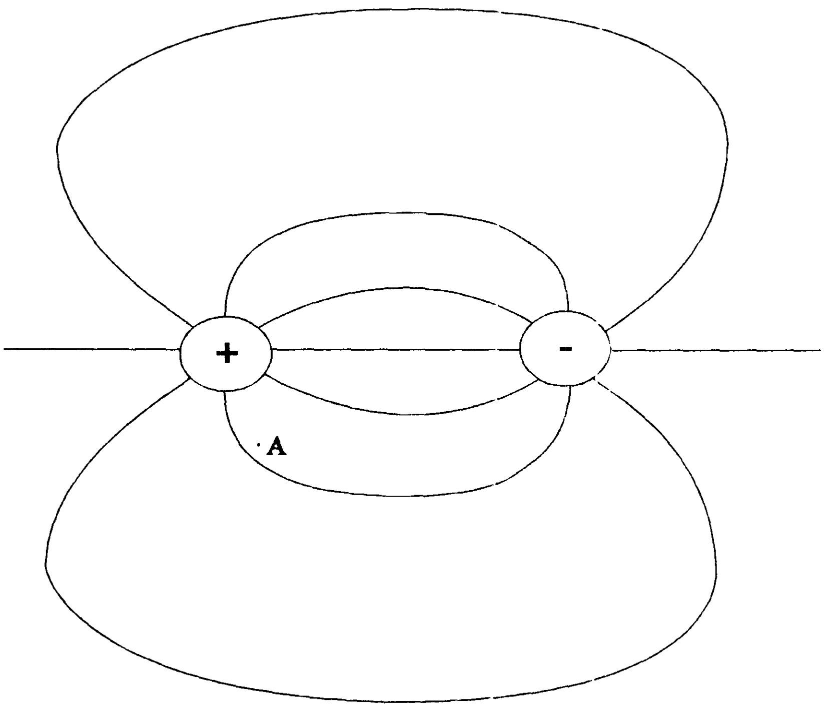
6) The plates of the capacitor in question 5) are spanned by a resistor. A current flows through the resistor but the capacitor is kept charged by the battery [see figure below, bottom diagram]. Draw the field inside the capacitor now. Explain why it is so.







7) A small positively charged particle is placed at point A [see figure below]. Draw its path. Why should it follow that path?



What forces are acting on the particle at a point X (half-way along its path to the negative charge)? Draw them. Draw the total force acting on the particle at this point.

Consider the velocity at this point. What forces are acting to make the particle follow the field line?

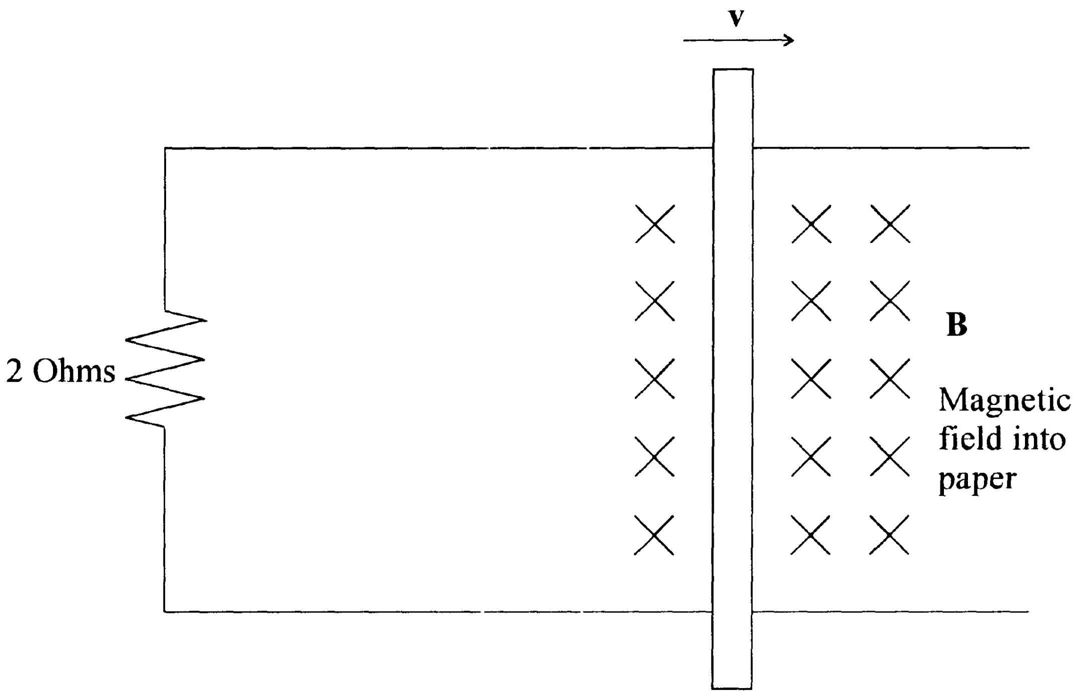
8) A charge in an electric field experiences a force of 3 N. What happens to the force if the strength of the electric field and the magnitude of the charge are both doubled? Explain why.

APPENDIX N

Schedule for interview 3.

QUESTIONS FOR INTERVIEW 3

1) [This question refers to the diagram below] The bar (50 cm long) is sliding at a speed of 2 m/s 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 the above before?

ii) How do you know which way the current will go in the above answer?

iii) What causes the current? How do the field lines of the magnetic field relate to the current?

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

v) Can you explain what's going on in terms of charges moving through the circuit? Why do they move?

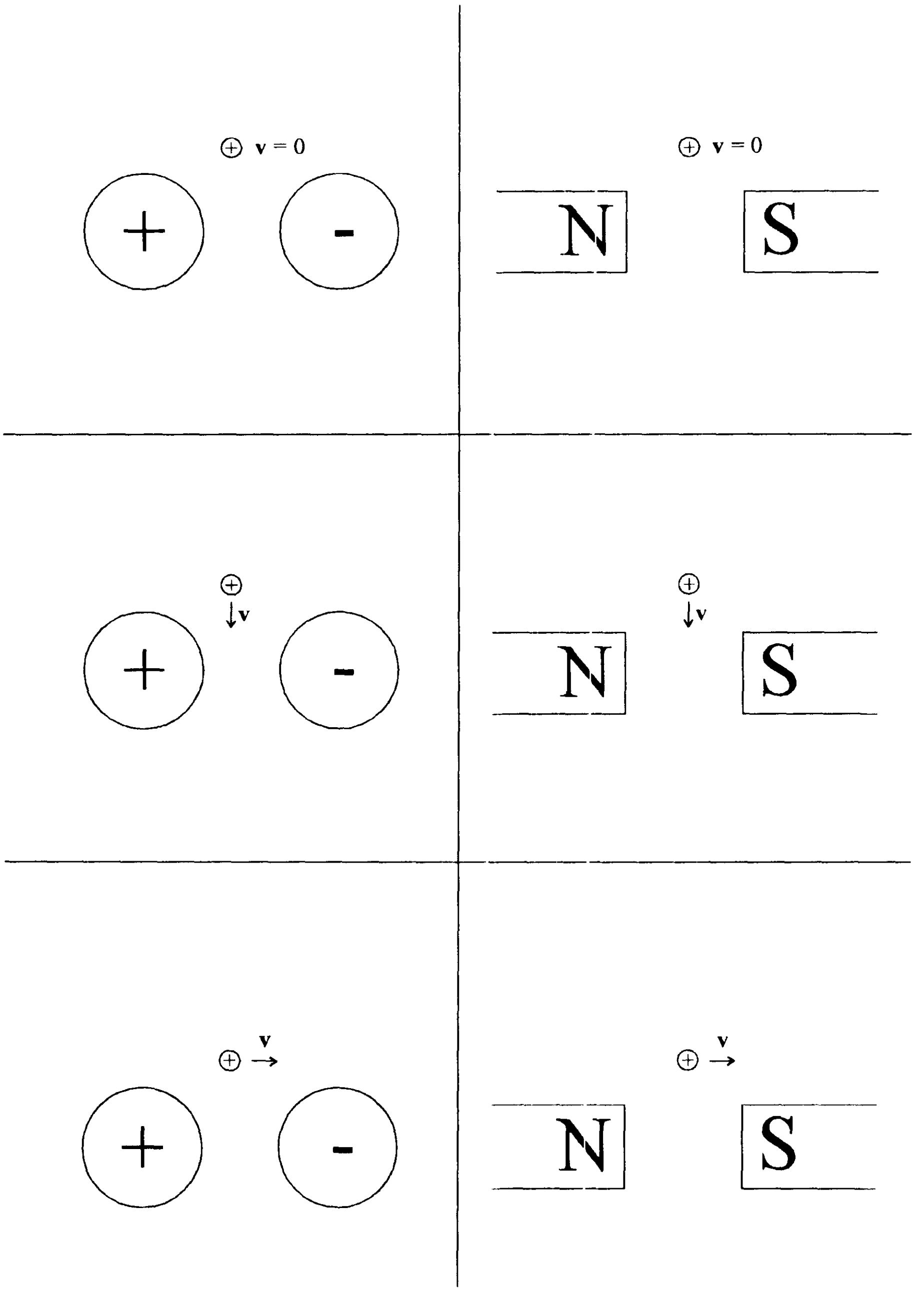
vi) (Using the same diagram as above) If the current through the resistance is measured to be 2.5 x 10(-3) A, and the speed of the bar is known to be between 5 m/s and 10 m/s then what do you know about about the magnetic field? The bar is still 50 cm long.

vii) The bar is moving through a uniform magnetic field as before but without the contacts. Is there a current? A voltage? What is happening in terms of charges in the bar?

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

ix) What happens in general if you move a wire through a magnetic field? What does this effect depend on? Explain why it happens. Does it depend on direction of movement, velocity, acceleration?

2) Will there be a force on the charge in the following situations, and in what direction [see figure below]? Predict the motion of the particle.



APPENDIX O

Details of students' responses to questions referred to in chapter 5.

These questions are, in order of appearance in that chapter and this appendix:

As in the text, "(s. 23)" in relation to a quotation indicates that it was spoken by student #23.

Question 2 of test/interview 1: A non-routine magnet

This question presented students with a picture of a round magnet, and asked them what sort of magnetic field it might have:

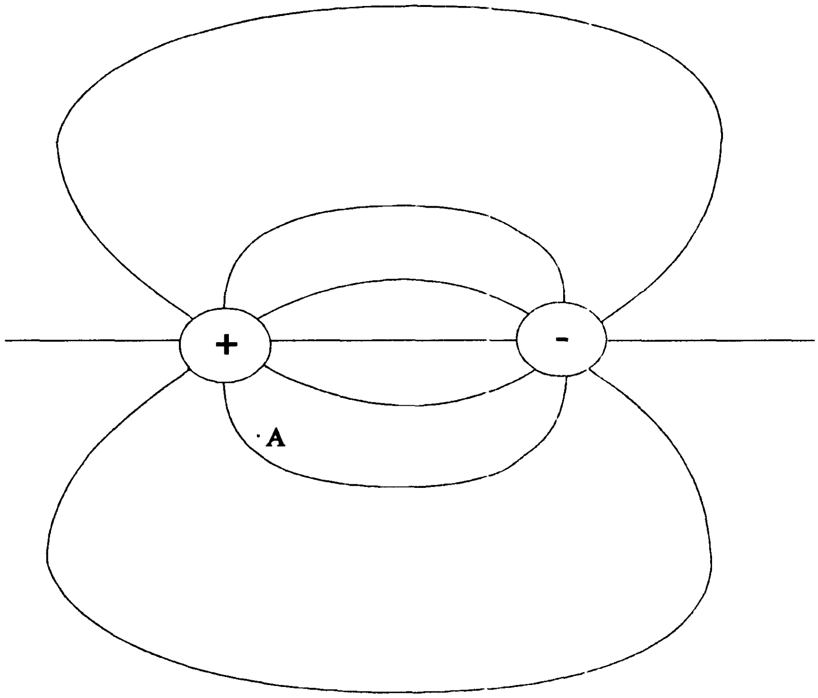
> *This is a round magnet. [diagram of toroidal magnet] What sort of magnetic field might it have? Sketch all possible magnetic fields and explain why they are possible.*

Students' responses to this question were predominated by simple memories of fields. Five of the students refused to answer this question, and ten others gave responses which were a direct statement of what they had seen previously, either the magnetic field of a current loop, which is not a possible answer, or actual patterns in iron filings near a round magnet. Another four students attempted to reason from inaccurate ideas, such as that the field had to be perpendicular to the surface, or that fields pulse outwards from a magnet.

Only nine students were able to reason about the north and south poles of the magnet, and to answer from there. Of these, only one had a relatively complete view of the constraints on possible north and south pole configurations in the magnet, with a consideration of the microscopic nature of a magnet.

The overall impression is that students applied a number of remembered facts to this question, many of which were inaccurate. Even those with accurate facts could not, in general, use them to reason about the possible magnetic fields of a round magnet. This corresponds to the difficulty which students had using these concepts in the preceding question about lines in iron filings near a magnet.

Question 5 of test/interview 1: particle trajectories



Charged particle in an electric field

In the diagram above, the circles with "+" and "-" signs are positive and negative point charges. Indicate on the diagram the path a small positive charge will follow if it is released at point A. Could the mass of the charge make a difference? (yes/no). Explain why or why not.

This question supplies a diagram with a finite number of "field lines" drawn. It was hypothesised that some students would predict that the particle would move from point A to one of the "lines" drawn in the diagram, in a similar way to their ideas about iron filings moving to a number of finite lines in the question just described. This response was not in fact common. It was also hypothesised that students would predict a movement of the particle along the field line which passes through A, and this misconception was very frequently seen in the responses.

<u>Concrete symbolic responses</u>

All the responses to this question were firmly concrete symbolic in SOLO terms. One student did not respond. Many students seemed to see the field lines as simply representing the exact paths that particles would follow in the electric field. That is, they saw the field lines as simple <u>symbols</u> showing the path, which is a <u>concrete</u>, directly observable object. A few students said that the mass and momentum of the particle would affect its path, which would hence not follow field lines exactly. However, as can be seen in the example response, their reasoning about momentum and inertia seemed to be quite naïve, using intuitive, Aristotlean mechanics.

A multistructural level understanding of the problem could lead to a number of different predictions for the behaviour of the particle. A total of 24 students responded at this level. There were a number of interesting sub-groupings here, depending on their treatments of friction, gravity and mass. The consistent aspect of all the multistructural responses was their failure to effectively integrate the field line idea with the mass of the particle.

Nine students in the multistructural group believed that if the particle is too massive then it won't move at all. These students seemed to be working from intuitive ideas about having to overcome static friction to start an object moving. They were not using the physics abstraction of a frictionless ideal case, as shown in this response (s. 33),

> F = m a. m up [hence] a down
> *Student: [reads aloud] "would the mass of the charge make any difference?" Yeah, um, well, I thought it did. Obviously if the charge was too great for the force acting upon it it wouldn't move, um, so I just thought that the mass would make a difference to it.*

This is a clear statement about the "obvious" fact in everyday life that a force has to have a certain minimal value to overcome the static friction holding an object in place.

> *Interviewer: Could the mass affect the path?*
> *Student: What I'm thinking is if the mass was substantial but not too great for the particle to move then the particle would still move within the lines of force towards the negative charge, so it would be more of a time factor rather than it actually deciding that it would move straight to it or out and round here or something.*

This student belived that the particle will follow "lines of force", moving "within" them. There is a certain concreteness about the idea of these lines, which form the paths of particles released in the field.

Another three students, also in the multistructural group, said that gravity acting on the mass will affect the path of the particle. While this is completely true, it again does not use a common physics idealisation, that of negligible gravity, e.g. (s. 38), "If the mass were significantly increased, the force due to gravity acting upon the charge could overcome the force from the electric field, changing it's [sic] path."

The idea that the force "from the electric field" could be "overcome" by some opposing force also appears elsewhere, with the force from the field even considered to be opposing the force from the charges producing it. This idea was held by another group described below in this multistructural category, who predicted that the particle would move straight to the negative charge if its mass was big enough. There seems to be an idea that the path is fixed, unless these forces are overcome in a catastrophic way - that is, the path will be followed exactly unless something is great enough to make it "jump the tracks" of the field lines.

Another nine students came up with a multistructural response that mass will only affect the speed of the particle. These students did appreciate the link between mass and acceleration, but did not seem to have a picture of the fact that motion is not necessarily parallel to force, e.g. (s. 44),

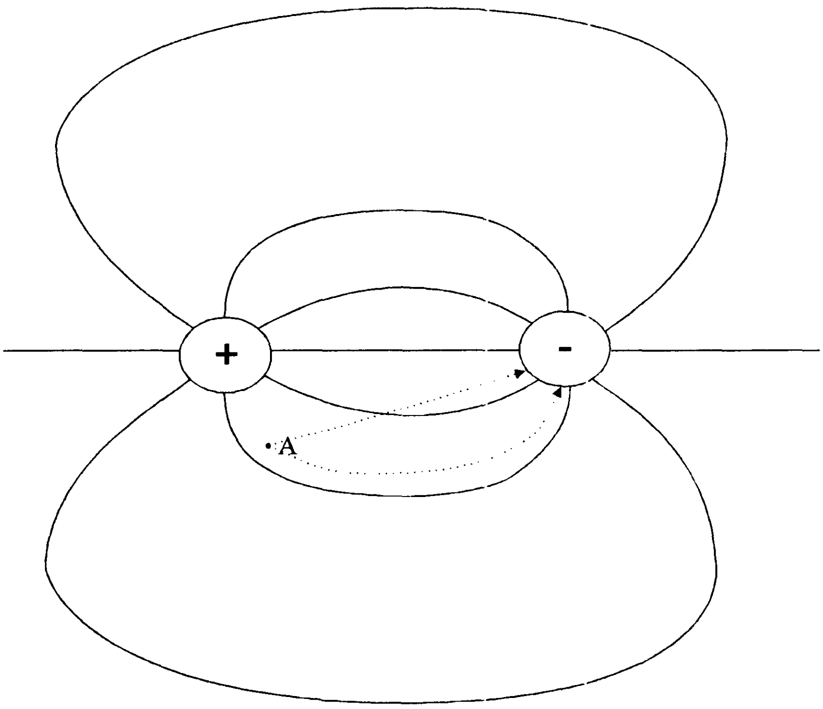
> *Student: ... Yeah, I was just going like Newton's second law there. F equals m a, like proportional to mass or something?*
> *Interviewer: O.K., and how do you know what the path will be?*
> *Student: I just said follow the electric field like from positive to negative.*

Interviewer: So how do you know it won't be a bit straighter or a bit more curved?
Student: I just went like parallel at each point of the electric field.

This is a simple identification of path with electric field lines. However, he did consider that mass would have some effect, and would change the acceleration.

Yet another multistructural form of response, from four students, was the idea that a massive charge moves straight to the negative. These students thought that a more massive charge at A might go straight to the negative charge in the picture. There was an interesting conflict in their minds between the concepts of particles being attracted to opposites and being influenced by fields. They did not seem to have related these two ideas satisfactorily, e.g (s. 19),

Interviewer: O.K., and will the mass of the charge make a difference?
Student: Yeah, the um, that's where the field lines come into it, I think ... The higher the field strength, the mass of this would be um, if it was like a really high field strength, it would flow into the um, field lines I'd say. But depending on the weight of this, with more mass ... it would be more moving straight towards it [student points at diagram].
Interviewer: [describing student's pointing over diagram] Moving straight towards the negative charge if it had more mass?
Student: Yeah.



Charged particle moves along field line or directly?

The above figure shows the two paths, curved and straight, which were competing in this student's reasoning. He appeared to view the field, which caused a curving path, as something separate from the effect of the charge as such, which caused a straight line path - this was a multistructural approach. It was also possible to come to a different conclusion, that mass alters path, through multistructural reasoning, as shown by two students. Their picture of field lines did not include an integrated picture of force, but rather an idea of lines that guide movement, e.g. (s. 17),

> Yes, with great mass sufficient momentum could be built up for the charge to be swept passed [sic] the (-) charge.
> *Student: Yeah, I just thought it'd follow the lines ... The small mass'd follow the lines, an infinitely small mass. But with a greater mass that momentum would mean that it'd follow the arc to a point and wouldn't stick with it, [student shows track with pen tip] it'd get [pause] centripetal acceleration? No [pause]*
> *Interviewer: When you say it'd follow an arc, is that like a train would follow a track and then jump off?*
> *Student: That's right, that's exactly right, that's exactly the point, that if it had infinitely small mass, like a train on a track on a curve, too much momentum being chuted off, tangential.*
> *Interviewer: So you mean it would stay exactly on track and then jump off?*
> *Student: It would stay on track with an infinitely small mass. It would stay on track for a while until it got to a point where it could tangentially shoot off.*

The reasoning here has the field line as a natural path which charges follow, but which they can break out of if they have sufficient "momentum". There is no clear consideration of forces and their relation to the field line.

Interestingly, the students in this last subgroup of the multistructural level came to the same conclusion as the students in the relational group which is next described. However, the reasoning used was quite different, with the multistructural groups emphasising the individual ideas of lines and mass, but not fully integrating them. Three students came to believe that the mass of the particle affects its path, using a relational level of reasoning. This involved a consideration of the relationship between the field lines, the force on the particle and its direction of movement.

The following excerpt (s. 32) was the most thorough description of the phenomenon at this relational concrete symbolic level. It relates the points in the multistructural response through consideration of the intuitive idea of inertia. The treatment of inertia is lacking in abstraction, and hence does not raise this response to the formal mode of the SOLO Taxonomy. However, the response has integrated the idea of field lines with this idea of inertia, and this resulted in some plausible predictions for particle movement.

> As a massive object begins to follow the path shown, it will gain momentum in its initial and subsequent directions and thus will follow a wider curve.
> *... The mass will definitely make a difference, because if you have a charge with infinitesimal mass as I was talking about before then it will follow exactly the field lines that I don't like talking about. But as the mass increases, it will have an initial acceleration and then it will keep some inertia, so if it has a small mass it will move immediately away from the positive charge, come out, maybe intersect with this field line and come back in <u>meeting the negative charge</u>, say from the right rather than at the bottom where the field line goes in.*

Here, the student is still assuming that the positive test charge will reach the negative charge. This corresponds to his "spiraling in" description below.

If it has a higher mass then it'll initially accelerate away from the positive charge, keep some inertia and as it's attracted towards the negative charge it'll have to keep going in the same direction it's been going before, so <u>it might spiral in towards it,</u> and the spiral will probably be wider on the right than on the left because you have a smaller influence from the positive point charge over on the right. I could be mistaken in this, but I think it's right.

This description of spiral orbits is indicative of intuitive mechanical ideas. Spiral orbits will only occur if there is some effect, such as friction, gradually reducing the energy of the particle. Otherwise, conservation of energy implies that the average radius of the orbit will not change. The idea of spiral orbits may relate to the intuitive physics assumption that objects tend naturally to come to rest, or perhaps to the intuitive idea that positive and negative charge will meet due to their tendency to neutralise one another.

...
Interviewer: O.K., so what are the effects of increasing the mass on the behaviour of the small charge?
Student: Um, it will accelerate more slowly initially, but once it's done so, it's going to keep going in its initial direction more effectively - stupid word to use. It's going to want to keep going in the same direction because of its inertia. So it will take longer to get to the negative charge and will follow a wider path to it, as I said, it might circle round.

The idea of "inertia" is used rather loosely here, and there is still the assumption that the test charge will reach the negative charge, even though "it will take longer" to get there.

<u>Summary of results from this question about particle trajectories</u>

Students fell short of the formal mode when describing field lines and particle trajectories in this question. They commonly believed that field lines represent the concrete paths taken by particles in the field, rather than the more abstract notion that trajectories do not generally follow field lines. This may tie to an intuitive mechanical idea that movement is always in the direction of total force (Galili, 1995).

Question 3 of test/interview 1: Predicting field interaction near two positive charges

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

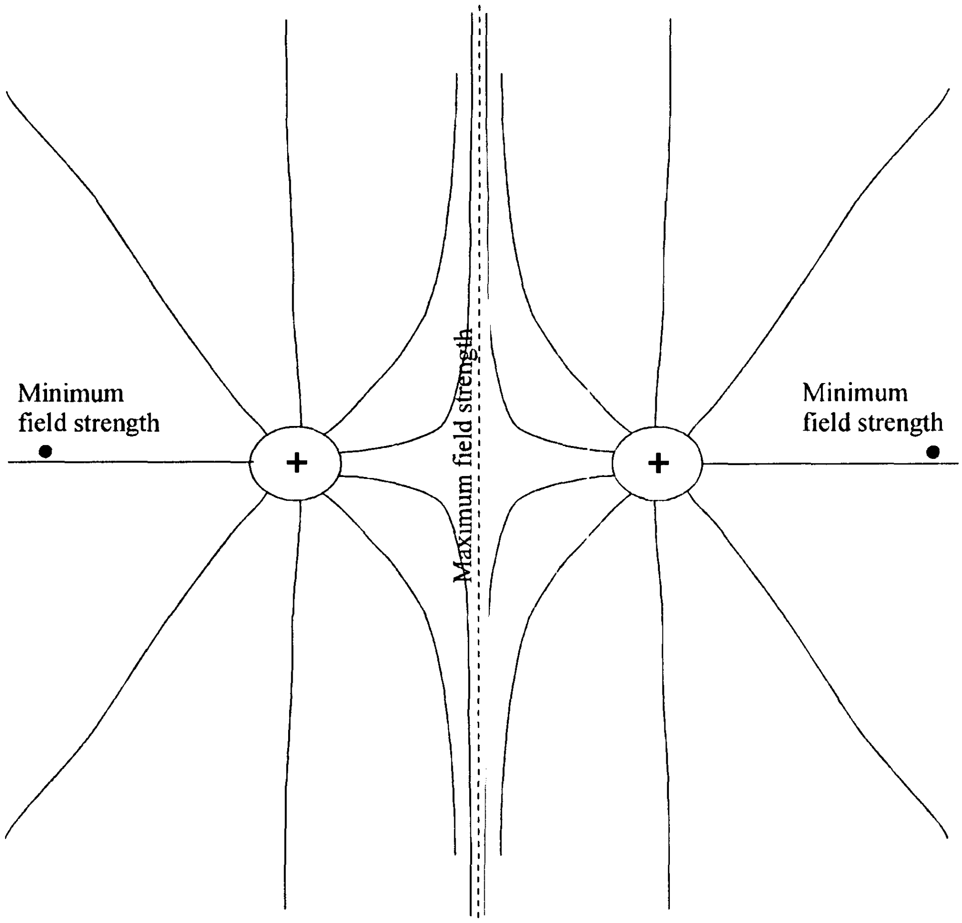
This question was intended to probe the nature of students' conceptions of field strength as it relates to field lines and the field vector. A second part of this question dealt with the minimum and the maximum of potential, and is described in the section of chapter 6 dealing with potential. Twenty-eight students answered this question.

Concrete symbolic responses to this question emphasised field repulsion and field lines, where the formal mode responses used the field vector and the equations for field strength.

Concrete symbolic responses

The distinguishing feature of this mode of response was a concrete picture of field lines or field which dominated reasoning. For the nine students responding at the multistructural concrete symbolic level, field lines were present in their drawings, but they did not use them consistently in their predictions, and there was no unification based on these field lines or on any other concept. In the example drawing and interview excerpt below, the student (s. 39) considered fields which push against each other, but did not use field lines or other more elaborate concepts:

> (a) [minimum] there are no other forces than the force from the individual point charge
> (b) [max] because the two point charges are working against one another
> *Interviewer: How do the fields of these two charges interact?*
> *Student: They repel one another.*

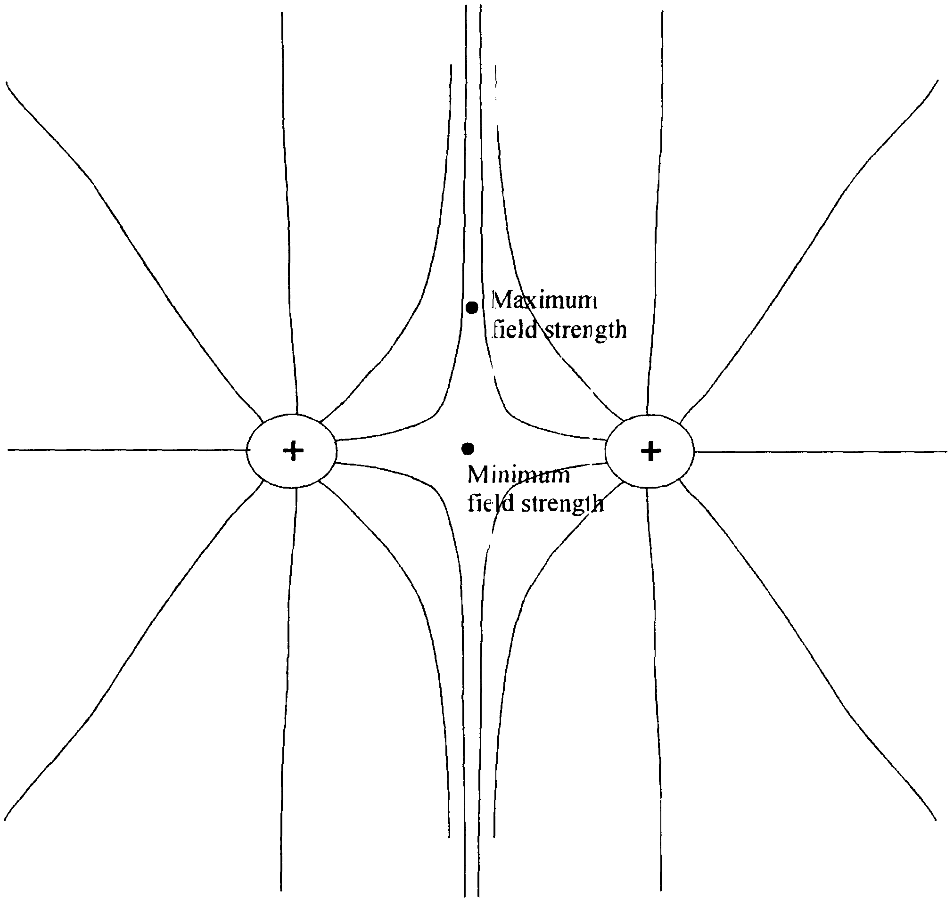


Student 39's prediction for field

The student does not have any detailed mechanism for the interaction of the two fields or for predicting minima and maxima. The next group were able to relate these issues in terms of field lines.

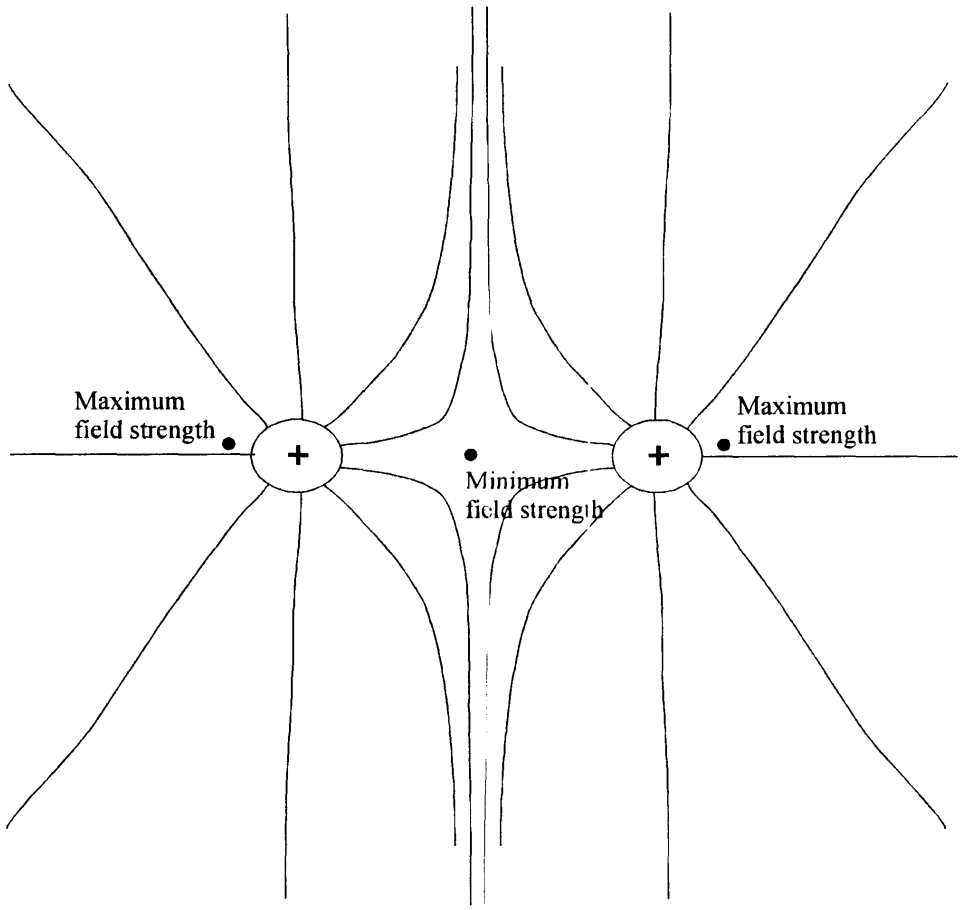
The twelve relational concrete symbolic responses used a consistent view that related field lines to field strength by considering the concentration of field lines, and unified their responses by doing so, as can be seen in the below quote and drawing from another student (s. 29):

> [min] (a) Fields repel one another and cause a gap
> [max] (b) fields are close together and parallel
> *Interviewer: What does it actually mean to talk about field strength? Like, you said where it's a minimum and a maximum, so what is actually a minimum and a maximum there?*
> *Student: Well, it's a minimum where there's fewer field lines close together and it's a maximum where there are more field lines close together.*
> *Interviewer: O.K., if you wanted to measure it at a point, could you do that?*
> *Student: [long pause] Well, you'd have to measure the number of field lines cut by something, [pause] like a wire.*



Student 29's prediction for field

The above quote equates field strength with concentration of field lines. This reasoning has led that student (s. 29) to predict a maximum of field strength along the line between the two charges in the figure above. The same sort of reasoning could lead to the prediction that the field strength would be maximum near a charge, as can be seen in another student's (s. 26) drawing and quote below:



Student 26's prediction for field

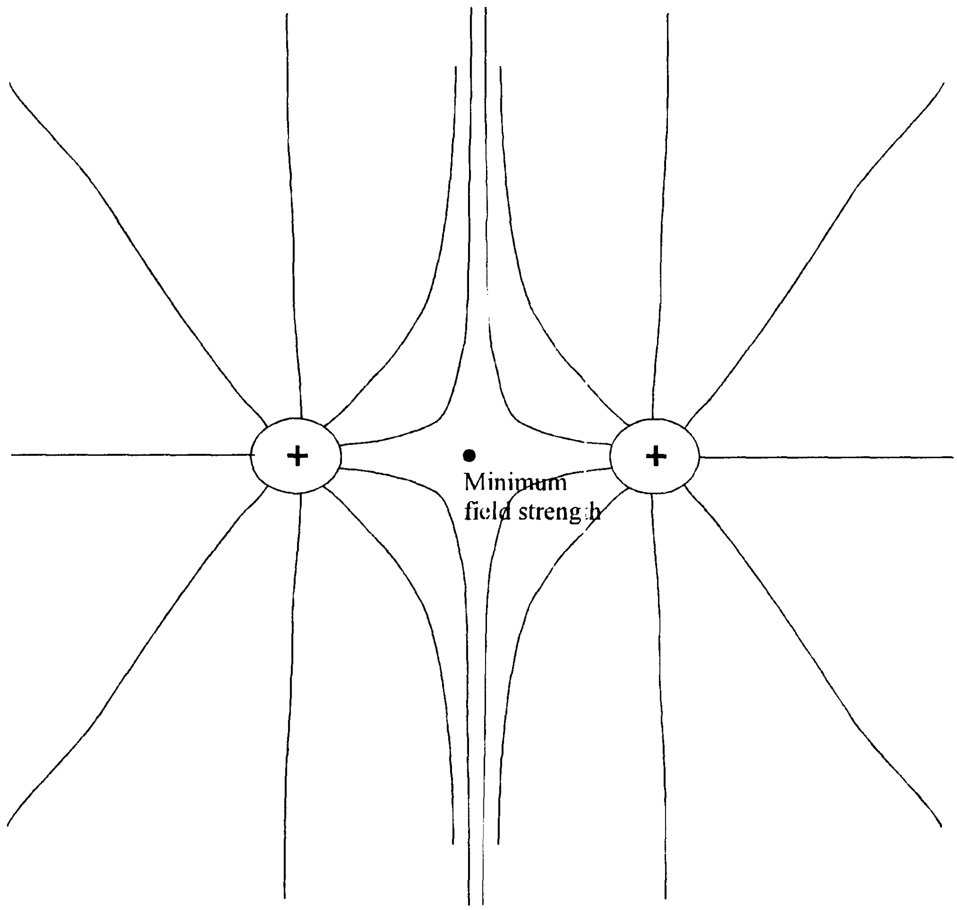
[min] (a) 2 fields add together -> space between field increase -> weaker
[max] (b) No field here so min strength. more lines -> stronger
Student: ... I put it there, because um there's no field lines at all, because there's field lines going through there, but here there's none at all, so they all become cancelled - since they're repelling each other, so they're bending away so there wouldn't be any at all there, so finally I realised that that one would be where the minimum would be, right in the centre between them. If they were the same strength, that is. Because out here they're still getting affected from those lines, whereas in here the lines all tend to turn out.
...
Interviewer: O.K., when you talk about field strength, what does that actually mean?
Student: ... Field strength um [pause] I dunno, field strength, how would you define that [pause] Just the number of lines that are close together, I suppose. The closer the lines are, the stronger the field would be at that.

This quote also focussed on the field lines, and predicted the field strength by using them. This relation between the concrete field lines and the concrete picture of field strength was characteristic of the relational concrete symbolic level of response.

Concrete symbolic responses were based either in views of the field line or less distinct ideas about fields. The formal mode views were able to use vectors and equations in their explanations.

Formal responses

Answers in the formal mode were able to answer questions without assuming concrete entities for their reasoning. Seven students displayed formal responses to this question. It was possible to fully answer this question without exceeding the unistructural level of the formal mode, by using the concept of a vector field. The student quoted below (s. 32) had the idea of field cancellation at a point, which is responsible for his prediction of a minimum in between the two charges, as shown in the diagram. He also reasoned with the equation for field strength, in which he took infinitesimal limits. There was a consistent ability to apply the abstract system of field vectors and equations in his answer.



Student 32's predictions for field

> [min] (a) The point Z will have a zero field because the fields of the point charges cancel one another.
>
> [max] (b) An infinitesimal distance from each charge because here the r^{-2} factor of field strength tends to infinity!

Summary of results for this question

This question showed that students were generally unable to use vectors and equations in their considerations of field strength near two point charges. A large number were able to come to a consistent prediction based on concentration of field lines. The field lines were the unifying feature for those students unable to use the abstract system of the field vector and field strength at points.

Questions 1, 2 and 3 of interview 2: Vector use in field interaction

Can you use vectors to represent electric fields?

Could you use vectors to predict the interaction of the fields from these two charges? [see figure below]

What is a vector?

Two positive charges

Students all replied that vectors could be used to represent electric fields, and had some sort of description of vectors, generally involving "magnitude and direction". The students' ability to actually use vectors varied; few students were able to actually use the vector picture to predict the interaction between the two fields. Their attempts to do so have been coded, and the SOLO categories found are presented below. A few students answered in the formal mode, with an ability to reason from the abstract vector picture, but it was most common for students to answer in the concrete symbolic mode, with vector ideas not being integrated into their picture of field interaction.

<u>Concrete symbolic responses</u>

The majority of students (15 out of 19) fell into this mode of response. These responses were characterised by an inability to use the concept of a vector field in reasoning.

Four of these responses were unistructural concrete symbolic, being unable to use vectors in field situations, with the only unit of reasoning being the proposition that vectors could (in some undescribed way) be used to represent electric fields, e.g. (s. 25),

> *Interviewer: Can you use vectors to represent electric fields?*
> *Student: Yes.*
> ...
> *Interviewer: Could you use vectors in a situation like this where we have two positive charges?*
> *Student: Um [pause] I dunno [pause] I don't think so.*
> *Interviewer: No?*
> *Student: No.*

This student had no ability to use vectors in his system of reasoning, which is centred on the undifferentiated idea of electric field.

The seven students responding at a multistructural level had the unistructural idea that vectors can represent fields, and added other facts about vectors, but still were not able to relate these to fields. They could not relate the ideas of field vectors and field lines, and their vectors were not clearly related to the field strength at any given point. Their ideas about field vectors were in terms of lines on a piece of paper, and lines in perpendicular directions (components), which are concrete symbols. These students were, however, unable to relate these to the system of field representation in any way, for example (s. 9),

> *Interviewer: O.K., so how does this diagram of arrows work in with this diagram of a line? What do they actually have to do with each other? ... you're saying that there'd be this straight arrow here and this straight arrow here and that they would in some way.*
> *Student: Connect to give the path [pointing on paper]*
> *Interviewer: [describing the student's pointing on the paper] To give the curved bit.*
> *Student: The path that it takes. That'd be the only way I could think of doing it.*
> *Interviewer: Could you see how they'd do that?*
> *Student: I couldn't picture it, no.*

The student quoted above was able to produce field lines, and also able to produce drawings of vectors on the paper. However, as he said, he "couldn't picture" how the connection would be made.

This contrasted to the four relational students, who were able to relate their drawings of vectors to the idea of field lines, but still lacked sufficient development of their ideas about vectors to use the idea of a vector field. They were unable to reason about field interactions using vectors, and their reasoning was based on concrete-symbolic field lines, e.g. (s. 39),

> *Student: A unit vector is [pause] one unit where that force was. I can't remember.*
> *Interviewer: O.K., so these curved things you drew here [the field lines], are they vectors?*
> *Student: Uh [pause] they're many vectors, I guess.*
> *Interviewer: Sorry?*
> *Student: Well, I sorta, when I think of a vector, I think of a straight line. To make a curved line, it's gotta be many vectors.*
> *Interviewer: O.K.*
> *Student: Many small vectors.*

In the abover, the student describes the many straight-line vectors making up the curved field line. This is a relationship between the two, rather like using many straight lines to approximate a curved line in a child's dot-to-dot picture. This simple relationship put the response into the relational concrete symbolic category. The following dialogue shows where this student fell short of the formal mode of response:

> *Interviewer: O.K., could you use vectors to predict the interaction of the fields from these two charges here?*
> *Student: [pause] Could you use vectors?*
> *Interviewer: Yeah*
> *Student: To find out the final vector?*
> *Interviewer: To find out, yeah, the final field. How would you do it?*
> *Student: Um, add 'em head to tail.*

This statement about "add ... head to tail" indicates an ability to carry out operations with vectors. However, further questioning showed difficulties:

> *Interviewer: Could you give an example?*

Student: That vector from there to there and that [draws one vector off each charge pointing towards the middle] - well, if that's a bigger charge
Interviewer: Just assume they're the same size.
Student: They should cancel.

This is true, but far from complete. It is not clear where or how the student sees the vectors cancelling. Further questioning revealed weaknesses:

Interviewer: Well, that doesn't tell you everything about the field, does it. I mean, you've said they'll cancel in the middle, can you use vectors to say anything else about the field?
Student: Um, I guess you can only plot points of a field using [pause] vectors.

This sounds hopeful, but as we see later, it is misconceived:

Interviewer: Plot points. What do you mean?
Student: [pause] Vector, so there, vector there, um, that's going to leave you with a point of your - you put 'em sort of in the middle of the two, it's going to end up sort of like that, so the result'd be there, I guess.

In the above quote, the student describes the drawing he is doing while speaking. He first drew diagonal vectors off each of the charges, then added these diagonals together directly between the charges. The point he comes to by adding these vectors is what he calls the "result", but it has no meaning. Further questioning shows this:

Interviewer: So what does that point you've just drawn mean?
Student: [pause] The addition of those two vectors.
Interviewer: O.K., so that's a point,
Student: The field at that point, oh, well, [pause] I dunno, that's where the field would be, I guess.

The "point" discussed above is a location between the two charges, which was where the two vectors added together finished. This student was able to relate vectors to field lines, but was unable to associate the vectors with a point in space. This left him unable to work using the abstract vector picture to perform additions of fields. This contrasts to responses in the formal mode, which worked within this abstract framework.

Formal responses

These four students were able to use the abstract picture of a field vector at every point in space, representing the strength and direction of the field. This use of the field vector can be described as a basic unistructural unit in the formal mode, and it was possible to answer this question completely without any need for further levels of processing in this mode, i.e., the unistructural formal level was the highest possible level of response to this question. Further cycles of growth would involve application of this principle of vector field superposition as a part of more complicated questions. The abstract picture of the field vector formed the basis of the students' reasoning about the interaction between the fields of the two charged particles, e.g. (s. 53),

Interviewer: Can you use vectors to represent electric fields?

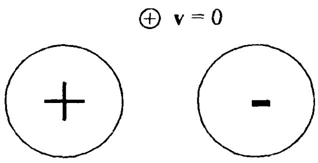
Student: [pause] Yep, you like an example for it?
Interviewer: Yeah.
Student: O.K., that's just a point positive charge, and at that point there, then [pause] the vector coming out of it for the electric field is going to be a vector somewhat like that moving at a straight line away from the charge - from the positive charge.
Interviewer: O.K., could you use vectors to predict the field associated with these two charges?
Student: Yep.
Interviewer: How?
Student: Well, [pause] the easiest example to start with would be if you just put one smack dab in the middle of em, so it's exactly in the middle, um [pause] call that charge one and charge two, the force acting on it - the electric field acting on it by charge one is represented by that vector, straight away from it, but then, if they're exactly in between and they're equal charges too, I should say, then the field acting on it from charge two is going to be a [pause] an equal vector in the opposite direction. So when you add the two of them together, your net effect is going to be a zero field, in the centre there.

Note that this student clearly associates the field vectors with a certain point in space, allowing use of the system to predict field interaction. As further questioning shows, he can do this at an arbitrary point as well:

Interviewer: O.K., what about at another point, such as here.
Student: Um, [pause] well, if you put it up there, it's closer to two than to charge one, so charge two is going to have a larger effect in it, it's going to be say moving that way, in a straight line away from charge two and a similar one, only a smaller vector, away from charge one, which means the net effect going to - it's going to move in that direction [pause] so if you're going to use another one, say in the same position down here, or say, rather than exactly in the middle of them, equidistant from the centre of it there, there're still going to be exactly equal vectors working on it, but charge two is going to be pushing it that way, charge one is going to be pushing it that way, so the net effect is going to be to push it away from both of them.

The overall impression from responses to this question is that only rare students are able to use vectors in their reasoning about this topic, even when asked specifically to consider them. Successfully answering the question required use of the unistructural formal concept of vectors , which was not available to the majority of students.

Question 2(a) of interview 3: Particle in an electric field



Test charge between positive and negative charge

In this question, students were asked to predict the behaviour of a charged particle placed between a positive and negative charge (see above figure). This is the same situation as they dealt with in questions discussed in chapter, namely, question 5 of test/interview 1 and question 7 of interview 2. There is less emphasis here than in those questions on the exact relation of the path to the field line, but it is nevertheless a very similar question. This part 2(a) of the question is not of great interest in itself, although it does serve to confirm the responses to those previous questions about particle movement in electric fields. The main function of this question was to serve as a contrast to the other part of question 2, which discussed particle movement in magnetic fields. That other part of the question is discussed in chapter 5, in the section about the field vector.

The majority of respondents were in the concrete symbolic mode for question 2(a). Examples of responses follow.

Concrete symbolic responses

The single unistructural concrete symbolic response focussed on the attraction of the test charge to the negative charge, to the exclusion of all other factors. The resulting prediction was that the test charge would move straight to the negative charge.

At the multistructural level, five students focussed on both the attraction of the test charge to the negative and the repulsion from the positive, but were not able to clearly explain any relation between the two, e.g. (s. 1),

> *Interviewer: Will there be a force on the charge in these situations, and where will it move to? Start with the first one.*
> *Student: [pause] There will be a force on that charge, and it'll move towards the negative, and it'll be - it'll be opposed from that [referring to the positive charge], that'll - they'll oppose each other.*
> *[this student drew a line straight to the negative charge to show the path of the test charge]*

This student has mentioned both the force from the negative and the positive charges, but has been unable to integrate the effects of the two, leading him to make the same prediction for charge movement as the unistructural concrete symbolic response above.

At the relational concrete symbolic level, four students came to a reasonable prediction for the movement of the test charge by use of the concrete symbols of field lines. This approach gave a consistent, though incomplete, view of the system, e.g. (s. 44),

> *Interviewer: ... Is there a force on the test charge?*
> *[Student drew field lines between the two given charges, and a tangent to the line going through the test charge]*
> *Student: Probably just [pause] crack out at a tangent to that, or [pause] something like that [pause]*
> *Interviewer: So can you draw in where it'll move to, or what path it'll follow?*
> *[student draws a heavy line along the field line from the test charge to the negative charge]*
> *Interviewer: O.K., so how did you draw that first line that you said the force would be tangent to?*
> *Student: Well, field line goes from positive to negative [pause] so, where that is, the force'll be a tangent to that.*

This response was completely centred on the idea of field lines. As seen in responses to other questions involving field lines, a view based on field lines relates the facts together without requiring the student to leave the concrete symbolic mode of reasoning for the abstract.

<u>Formal mode responses</u>

These respondents were able to use the unistructural formal concept of superposition of field vectors. Five students responded at this level, e.g. (s. 29),

> *Interviewer: ... can you say what force will be on the test charge?*
> *Student: Well, there will be a force [pause] directly away from the positive charge and another force [pause] directly towards the negative charge, which means if you add these [pause] tip to tail, you get something that's sort of this direction initially.*

This student used the vector model to predict the force on the particle, rather than reasoning from ideas of attraction or field lines as did the students responding in the concrete symbolic mode.

Overall, student responses to this first part of the question were consistent with their answers to similar questions which were dealt with in more detail earlier in the thesis.

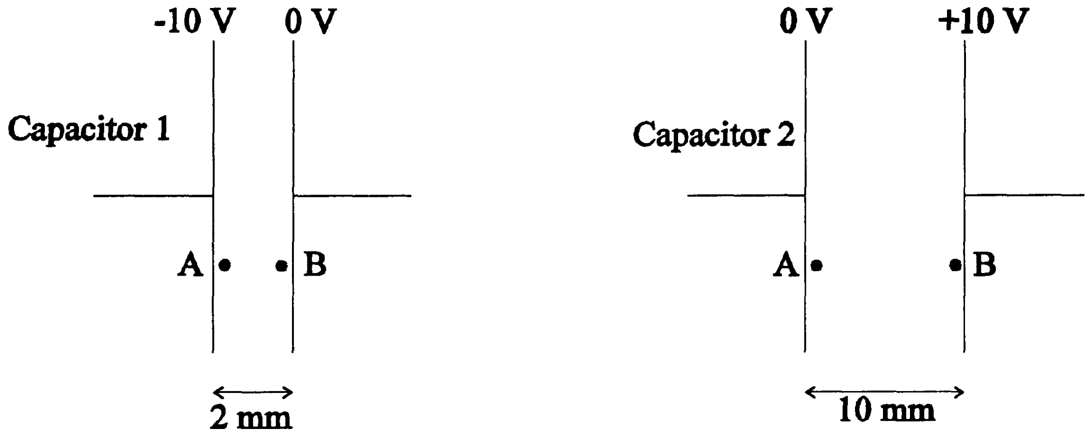
APPENDIX P

Details of students' responses to questions referred to in chapter 6.

These questions are, in order of appearance in that chapter and this appendix:

Question 6 of test/interview 1: Potential, potential energy and kinetic energy

Responses to other questions about potential showed that students tend to identify it with field strength and have difficulty relating it in detail to electric current. This question is concerned especially with the relationship between potential and energy for a charged particle moving in an electric field:



Given capacitors

In each of the capacitors above, an electron is placed at point A [near one plate]. The electric field then accelerates the electron until it hits point B [on the opposite plate]. Compare the speeds of the electrons when they hit point B in capacitor 1 and capacitor 2. Explain the reasons for your answer.

In writing this question, it was intended that students consider the identical voltage across the two capacitors, and to relate this voltage to the kinetic energy of the electron. In fact, there was little range in the answers, and the vast majority of students (21 of 28) reasoned from the idea that voltage was identical to electric field, and that the field strength in each capacitor was therefore the same; from this, they concluded that the speed of the particle would be higher in the capacitor with greater spacing. Here is an example of this reasoning (s. 22):

> Speed from Cap. 2 would be 5 times greater than that of Cap. 1. This is from the distance being 5 times greater while the p.d. is the same.
> *Interviewer: Could you think about that question in terms of potential energy?*
> *Student: [long pause] Actually, I think I've got the right answer there, because the potential energy would be greater.*
> *Interviewer: How do you know that?*
> *Student: [pause] because it's got a greater distance to go, it's like having two stones held at two different heights, the one at a greater height has a greater potential energy because it's got a greater distance to fall - a greater distance over which it can accelerate.*

The above reasoning is fully consistent with the commonly held view that potential and field strength are identical.

Only seven of the 28 students were able to reason about voltage as being equivalent to energy rather than to field strength. An example of this follows, (s. 32):

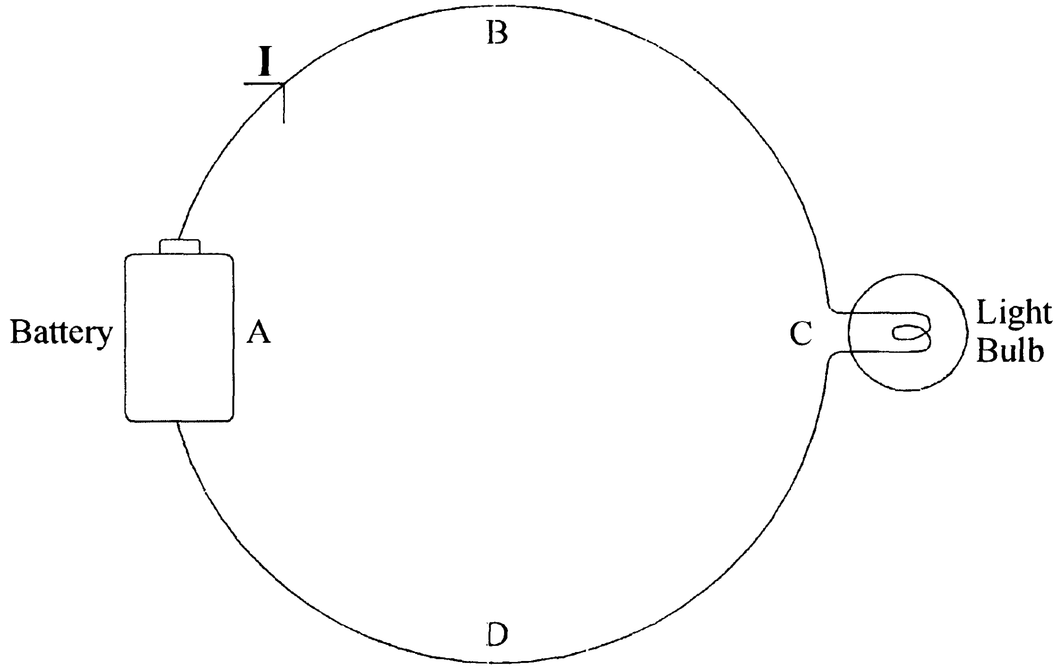
As energy = q V and energy = (1/2) m v^2, and q, m and V are constant for both experiments, v will be exactly the same.

This student was asked questions to test his certainty in the interview:

Interviewer: O.K., so given that one has five times as far to accelerate as the other, would you still expect them to have the same speed?
Student: Well, the potential difference that we're talking about is the amount of energy they're going to pick up ... both electrons are the same mass, both electrons have exactly the same charge, and as mass is half m v - no, energy is half m v squared, as I've written there or the kinetic energy is, we're not talking about mass energy, but we don't need to worry about annihilations and that sort of thing. Um, The energy as the electron reaches B will be the same in both instances, therefore the velocity will have to be the same.
Interviewer: O.K., so how does it manage to have the same velocity after having accelerated over a longer distance?
Student: It's not been accelerating by as much.

The level of understanding displayed in the above quote was very rare in the sample. It seems likely that the ability to use energy considerations here has a formal abstract quality, although the limited range in the responses makes it impossible to identify levels in them. Generally speaking, students were unable to explain the relationships between potential, field strength and energy.

Question 9 of test/interview 1: Fields from the current in an electric circuit



Given circuit for prediction of field

Would you expect any difference in the strength of the magnetic field caused by the current at points A, B, C and D in this circuit? [see figure above] Explain exactly what you would expect and why.

The above question was intended to probe the effect of the students' ideas about current on their predictions about magnetic fields of that current. In fact, the students' predictions about the field in this case were based squarely on their ideas of current.

Five students declined to answer this question. Ten of the students predicted that the fields around the different parts of the circuit would vary, based on their ideas about current consumption in circuits, for example student 53,

> The magnetic field would be greater at A, B, C as some of the current is lost in the light bulb. Therefore, there is a smaller field at D.

The above shows the results of a misconception about consumption of current into predictions about the magnetic field of that current.

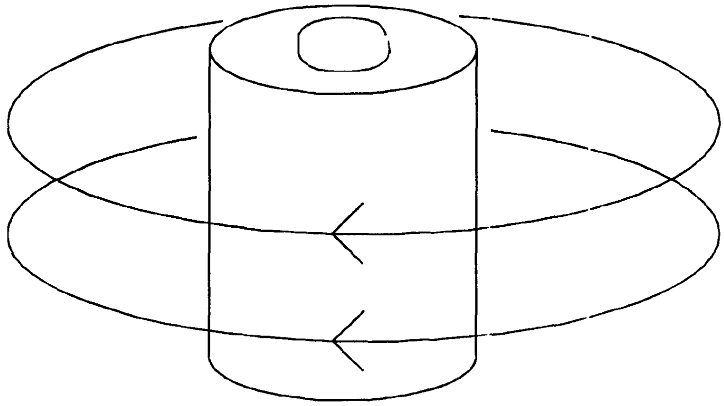
Thirteen students said that the fields would be the same, based on the current being the same at all points, as in the below response (s. 17),

> No [difference]. Same current throughout circuit and so the same magnetic field.

This is another straightforward example of ideas about current being reflected exactly in ideas about fields of that current. There was little complication in any of the answers to this question. The simplicity of the responses indicates that they are all a low level in the concrete symbolic mode. There is the overall impression that the students' ideas about current carry on into their predictions about the magnetic fields caused by that current in a circuit. The following question was concerned with their ideas about magnetic fields near a battery out of a circuit.

Question 10 of test/interview 1: Fields of a battery

A student drew the diagram below and suggested that a battery should always have a magnetic field around it when it wasn't in a circuit. Comment on this idea.



Suggested field around a battery

The students focussed either on the absence of a circuit, or on the idea of an electric/magnetic field for the battery in all cases. Many students confused electric and magnetic fields.

Six students did not respond to this question. Twelve of the students said that the absence of a circuit would mean no current and therefore no field, as did student 1,

> This [the magnetic field] cannot happen because there is no current flowing in the battery.
> *Student: That [magnetic field shown in the question] is not correct, because for a magnetic field to be induced you need a current, you'd have to continue the circuit and make a loop. You'd have to have a current running through the battery to have a magnetic field. You can't just have a magnetic field from a [pause] stationary current.*

This student had an idea about current being needed, and no further development.

Ten of the students were confused about the difference between electric and magnetic fields, which led them to suggest that the battery should indeed have a magnetic field while out of the circuit, for example (s. 22),

> This is true since there is a p.d. between the ends of the battery and thus a field associated.

This identification of magnetic field and p. d. [potential difference] is interesting, and shows confusion between electric and magnetic fields, as comes out in the further questioning below.

> *Student: ... I'm not really sure, there isn't really a current flowing in the battery because it isn't hooked up to a circuit, so there wouldn't be any electric field due to*

current from the battery, flowing. I don't know about the potential difference, I suspect there might be a field caused by that.
Interviewer: O.K., would you expect it to look like the drawing?
Student: Um, if anything, I'd expect it to be round like that [draws dipole field from ends of battery].

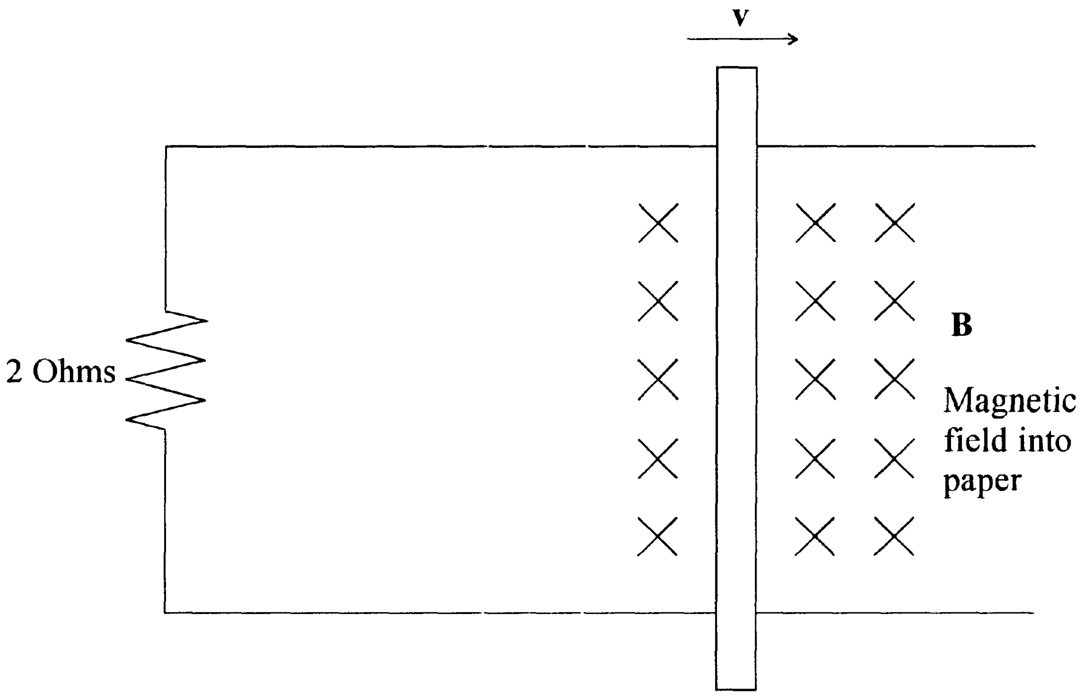
Here, the student has drawn the electric field of the battery, rather than the magnetic. The following question was intended to find his prediction for a situation where the battery has both an electric and a magnetic field:

Interviewer: O.K., so what happens when you put it in a circuit?
Student: Um, when you put it in a circuit, I'd expect it to [pause] get the same field as what they've got drawn there, due to the current.
Interviewer: O.K., and what happens to the field you drew before.?
Student: I would think it would break down due to the field caused by the coil, sorry, by the circuit coming out each end, by the current.
Interviewer: Would you see any difference between an electric and a magnetic field?
Student: I don't know, he didn't define them specifically.

Here, we see the student unable to distinguish electric and magnetic fields. This was a common failing in student discussion about the field of a battery.

As a general statement, students' ideas about circuit phenomena did come through in their predictions of associated fields. This reasoning from circuits to fields was seen consistently in the above questions. This shows that students' understandings are not completely compartmentalised in this respect.

Question 1 of interview 3: Induced current and its relationship to understandings of fields



Situation causing an induced current

This question was in several parts. Questioning ran as follows, with both written and verbal components:

(0) [Written, with diagram above] 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 2.5×10^{-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 verbal questions are aimed particularly at students' qualitative understandings of the causes behind the induced current in this case. Overall responses to this question as a whole are summarised in chapter 6, in the section dealing with currents. That summary also includes details of responses to part (vii) of the question, dealing with induction in a non-routine situation. Responses to part (viii) of the question are discussed in chapter 5, in the section dealing with flux. Details of responses to the other parts of this question are discussed below.

Question 1 of interview 3, parts (0) and (vi): Quantitative calculation

Students' performance with quantitative equations was based on memory of formulae. While the majority of students (9 of 15) said that they had seen such questions before, few students were able to answer the basic question, much less the extended one. Understandings were largely concrete symbolic and incomplete.

(0) [Written, with diagram (figure 6.6)] 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?

(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).

Students generally were unable to answer even the first part of the question, much less the extension part. As a result, their responses to the extension question were of little interest and are not discussed here. Below follows a discussion of responses to the main written question, part (0). Three students refused even to attempt this simpler question of part (0).

Concrete symbolic responses

The four students who responded at the unistructural concrete symbolic level each produced a single equation, but had no ability to relate it to the question. The equations used by these students all involved force, presumably because these were the equations they could remember. An example is given below (s. 44),

> *Student: I'd go something like - oh, what's that equation, something equals b l v [pause] I think that's an equation, I think it's just force equals b l v or something [pause] I dunno how that'd help, but [pause] what is it, force? [pause] Does something equal b l v? [pause] Yeah, it's kind of familiar.*
> [writes] F = B l v

That single equation was all that this unistructural student could produce. The five students responding multistructurally in the concrete symbolic mode used two equations for force, but couldn't answer the question from them, as in this response (s. 52):

> *Interviewer: Have you seen questions like that before?*
> *Student: Yeah.*
> *Interviewer: Do you think you can do that question?*
> *Student: Um, I can't remember the formula. Can you tell me the formula, it's a given type thing, f equals q v b. q v cross b [pause] b equals um [pause] b i l, I think, isn't it?*

Here the student has produced some equations, but no connection to the situation. The next question encourages the student to go further:

Interviewer: Um, what would that tell you?
Student: You've got to work out the current [pause] yeah, you've got to work out the [long pause] at the moment, no, I couldn't do it - I can't remember the formula.
Interviewer: O.K., what were those two formulas you mentioned before? Could you write them down?
[writes] $F = q v B$
$F = B I l$
$q v B = B I l$
$q v = I l$

That is as far as this student could take the calculation, as no useful relationship can be found from these two equations with which he started. The two students responding at a relational concrete symbolic level were able to come to a reasonable answer by use of conventional formulas for the problem, as in this response (s. 24),

Student: ... yeah, you work out the um [pause] one of the equations for [pause] inductance [pause] like, [pause] inductance, I think that's what it's called, isn't it, induced field? [pause] like, I mean - induced - make electricity [pause] make a current.
[writes] $emf = v B l = 2 \times 10^{-4} \times 0.5 = 10^{-4}$ V
$V = I R$
$I = V / R = 1 \times 10^{-4} / 2 = 5 \times 10^{-5}$

This student has been successful in the question simply by choosing the right equations and making substitutions. This was sufficient to answer the question, and is in the concrete symbolic mode of reasoning. One student could not remember this straightforward solution, and was forced to use abstract formal mode reasoning to reach a solution, as described below.

<u>Formal responses</u>

This single student (s. 32) answered the question in terms of the unistructural formal concept of magnetic flux. He only did so because he had forgotten the simpler, relational concrete symbolic means of answering the question. His overall knowledge of the subject allowed him to answer the question in a novel way:

Student: Webers per second are volts [pause] so, potential difference, and I want to know - I can talk about an area we're sweeping through now [pause] so, over the course of a second, we sweep through an area of one square meter, and [pause] being through a magnetic field of ten to the minus four teslas, gives us ten to the minus four webers per second, which isn't a very large voltage at all, so there must be something wrong, unless you've deliberately set it up so that there's a very small [pause] current flowing.
[writes] $T\ m^2 = Wb$
$V = Wb\ s^{-1}$

10^{-4} Wb s^{-1} = 10^{-4} V
V = I R
I = V / R = 10^{-4} / 2 = 5 x 10^{-3} A [note arithmetic error here, should be 5 x 10^{-5} after division by 2]

This student has an ability to reason in terms of the meanings of the units such as Wb, and to apply this back into calculations. He has reasoned from the assumption that webers per second are volts, and manipulated the equations from there. He has also considered the general magnitude of the numbers involved.

The quantitative aspect of this question could be approached through simple substitution into equations but few students were able even to do this. This parallels the results of their attempts at other quantitative questions, as discussed in chapter 4, which also showed a lack of use of principles in manipulation of equations. Their understanding of the principles behind the qualitative causes of the current is of interest, and is treated in the other parts of this question.

Question 1 of interview 3, part (iii): Cause of current

Why does a current flow?

This is the most direct question aimed at students' understandings of the cause of current in this situation.

It is possible to understand the induced current here at a number of levels. At a concrete level, one can use a rule of thumb to say that moving a wire in a magnetic field causes a current. One may also be able to relate this to the charged particles in the circuit. Only a few students were able to actually reason in terms of the charged particles in the circuit.

In terms of concrete and abstract concepts, most students were reasoning with concrete ideas, and surface aspects of the problem.

Concrete symbolic responses

The five students responding unistructurally focussed on the fact that there was a current, and that this was simply because of the movement of the bar in the magnetic field. This idea of "movement" was not developed, and no further explanation was given, as can be seen in this response (s. 56):

> *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.*

The word induction is used here, but no explanation is given; the word does not clearly have meaning for the student. The two multistructural concrete symbolic students added the idea that the current would have direction, though there was still no clear link between current and direction, and no idea of the bar crossing the field, for example (s. 53),

> *Interviewer: O.K., how do you know there's going to be any current at all?*

Student: Um, because [pause] well, there's a bar moving through a magnetic field, so you'd have a current [pause] there's got to be a coil, there's got to be a length of wire, moving through the magnetic field, which is what's happening [pause] and [pause] just the action of this bar, or what is it, bar, yeah, sliding through the magnetic field, is going to generate a current.

...

Student: Well, the actual strength, the actual direction of the field um, doesn't affect the actual value of the current, it just affects the direction in which the current will move. Coz in the picture here, the magnetic field [pause] is heading into the page, and if it was coming out of the page, as in, moving a hundred and eighty degrees to what it is now, then the current'd be the reverse of what it is.

The three relational concrete symbolic students related to the current in terms of field lines. They integrated the ideas of movement and direction in terms of a need for the bar to cross field lines in order to cause induction. There is a certain consistency in this approach, with the field lines as a usefully concrete concept for students to rely on to integrate their understandings, as in this response (s. 1),

Interviewer: O.K., what actually causes the current?
Student: The movement [pause] in the magnetic field and the change in the length - the movement of this piece of [pause] metal through this field.
Interviewer: So does any movement in a magnetic field cause a current?
Student: No, it's gotta be across the lines [pause] that's across the magnetic field lines, and it can't be - The magnetic field can't be moving with it, it has to be relative, moving relative to the magnetic field.

Formal responses

The five students in the formal mode were capable of explaining the current in terms of the particles in the circuit. The unistructural abstract model of particles causing phenomena was sufficient to answer this question. These students used this abstract model consistently, as in this response (s. 29),

Interviewer: O.K., how do you know that there will be a current?
Student: Because the bar's moving through at right angles to the field.
Interviewer: So?
Student: So there's a force on the electrons inside the bar.
Interviewer: O.K., how does that force come about ?
Student: Well, the force [pause] is [pause] f equals b cross v.
Interviewer: O.K., and what does b cross v mean?
Student: Well, that means [pause] that the field and the uh [pause] direction of motion, or the velocity, are at right angles, to one another, the cross, and therefore the force is at right angles to both of them.

In the above, the student reasons directly in terms of the forces on the charged particles within the bar, which he describes in terms of the forces on the individual electrons. There is consideration of the effect of the field at each point in the bar, which is causing the effect on the electrons.

Unlike the student last discussed, most students used simple rules in responding to this question rather than reasoning abstractly in terms of the behaviour of charged particles.

Question 1 of interview 3, part (iv): Effects of the induced current

Does the current cause any effects of its own?

This question was intended to see if students were aware of the feedbacks involved in the movement of the current, partricularly concerning Lenz's law and its relation to energy conservation. Responses were generally simple. Many mentioned the magnetic field of the current, with some also mentioning other features. While a few students had some idea resembling Lenz's law which described an "opposition" to the existing field or movement, there was no consistent reasoning behind these answers.

Three students were unable to describe any effects of the current, for example (s. 25):

> *Interviewer: In fact, does this current that's produced cause any effects of its own?*
> *Student: [pause] What kind of effects?*
> *Interviewer: Well, any effects at all?*
> *Student: On?*
> *Interviewer: Well, on anything?*
> *Student: No, I dunno.*

Concrete symbolic responses

The four unistructural responses concentrated on a single effect of the current, such as the magnetic field, as in this response (s. 54):

> *Interviewer: O.K., now does the current cause any effects of its own?*
> *Student: [pause] Yeah, a um [pause] oh, hang on [pause] the current's not changing, so it's [pause] when it induces a magnetic field, changing current induces a magnetic field [pause] but there will be a certain magnetic field associated with the actual current going through the wire.*

The five students responding multistructurally mentioned a number of effects, but did not relate them, for example (s. 53):

> *Interviewer: O.K., does the current cause any effect of its own?*
> *Student: Um, well, the current's going to cause an electric field round the wire as well ... probably moving through the resistor too, there might be a bit of um there might be a bit of heat from it being pushed through the resistor, but [pause] um [pause] I think that'd be about all.*

The three students responding relationally in the concrete symbolic mode described the effects in terms of some sort of reaction or opposition to either the existing field or the movement of the bar. This reaction/opposition was the principle which these students used to unify their answers. There was, however, no consideration of the abstract reasons that this reaction or opposition should exist, as in this student's (s. 29) answer:

> *Interviewer: O.K., does this current cause any effects of its own?*

Student: Yes, it [pause] attempts to [pause] stop the motion, coz the force is Newton's force [pause] Newton's law, one of Newton's laws, that an opposite [pause] force
Interviewer: Sorry, so the current tries to stop
Student: Stop the motion through the field by creating a [pause] a force in [pause] against the motion.
Interviewer: And you said that was one of what laws?
Student: Well, it's based on one of Newton's, equal [pause] every force produces an equal and opposite reaction. Every action produces an equal and opposite reaction.

The above mentions reaction as an integrating principle, and also Newton's laws, but does not mention the ideas of energy which are responsible for this idea of reaction. It was, however, substantially above average among the responses, and most students focussed on only one effect of the current, or a few unrelated effects. Only a few students were able to give any sort of integrating relationship into their explanation. The next question was intended to allow students to integrate all aspects of the question in their own words:

Question 1 of interview 3, part (v): Use of particle model

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

This question explicitly asks the students to use the model of charges in the bar in their answers. While students were generally able to mention charged particles in their responses, few were able to use them to reason about the situation. The majority of students made statements about charged particles which were based on the predictions they had earlier made by applying rules about circuits. There was no marked improvement in answers over the question just described.

Concrete symbolic responses

The three students responding at a unistructural level were unable to relate particles to the situation. As one put it, "I can't explain at all". Their unit of thought was the existence of a current or the non-existence of a circuit. The four students who responded at a multistructural concrete symbolic level could bring in the idea of charged particles, but were not able to use this in their reasoning about this situation, for example, this response (s. 17),

Interviewer: O.K., can you explain what happens in terms of charges moving within the circuit?
Student: [pause] current flow [pause] what, the interaction with the system as a whole, [pause] just my little current, little charges moving along.

In the above, the student has mentioned "little charges", but is not reasoning with them, and not making it clear exactly how they relate to the current situation. Further questioning attempts to clarify this:

Interviewer: Well, in terms of individual charged particles moving within the circuit.
Student: Yeah [pause] oh [pause] well, you've got a free electron for every atom, coz you've got a conducting metal here. We once looked at uh [pause] drift velocity, the velocity with which an actual charge gets moved along, it's incredibly slow, so

the problem comes up how does a light come on at the other end of the desk so instantaneously, it's because they all transfer, so they're interacting with each other and the charge just gets hit along, kind of, and uh [pause] flow of electrons is a bit of a misnomer, apparently, it's just the interaction between electrons that transfer charge - transfer energy. Well, actual electrons stay in place.

In the above, the student has brought in a large range of concepts: conducting metals, drift velocity, energy and interaction between electrons. However, there is nothing to relate them firmly to this particular situation. Further probing reveals deep confusion:

Interviewer: So why do these electrons move?
Student: Why do they move, [pause] um [pause] energy.
Interviewer: Could you give more detail there?
Student: Possibly not [pause] I think I might be able to um [pause] no.
Interviewer: In this particular case, what do you think's making the electrons move?
Student: [pause] I would say it could be um [pause] that there's repulsion going on there?
Interviewer: From what?
Student: Not sure [pause] um, I'm trying to work it out [pause] the force being exerted on them, perhaps? [pause] by the magnetic field? [pause] no, not that.
Interviewer: Why not?
Student: Inductance! They're getting pulled through.
Interviewer: What does inductance mean?
Student: I've got no idea, didn't cover that particular topic.

In the above, the student is coming up with a broad range of disjointed concepts which apply only marginally to the particular situation.

The two students responding at a relational level in the concrete symbolic mode had the idea of particles being moved by some sort of effect, but were not clear as to how the effect came about, as in this response (s. 53),

Interviewer: O.K., can you explain what happens in terms of charged particles moving in the circuit?
Student: Um [pause] what happens is um, when the bar moves, it creates electric current, what the electric current really is is the movement of negatively charged particles called electrons which move in the opposite direction to the way the current goes, for some reason, makes it really irritating when you're doing these questions, but [pause] they represent the electric - sort of the flow which the current is supposed to be.

In the above, there is a clear relationship between the current and the particle movement, but the student is reasoning primarily in terms of the idea that "when the bar moves, it creates electric current". From there, there is a statement about "negatively charged particles called electrons", but the decision about current flow has already been made by that point. This contrasts to the overview in terms of charged particle behaviour seen in the formal answers described below.

<u>Formal responses</u>

These six students were able to use the unistructural formal system involving charged particles to reason about why the current should exist. Their primary reasoning was in terms of the particles' behaviour, which then let to predictions about current, rather than the reverse which was the approach in the relational concrete symbolic answers discussed above. An example of this unistructural formal group is given by student 52:

> *Interviewer: O.K., how do you know there will be a current?*
> *Student: [pause] coz of, um, coz of this formula, force equals q v cross b, in the direction, um, the force on the electrons [pause] coz the electrons in the bar, they're going to be, coz the force is going to move with the - they're going to move up or down the bar, [pause] v cross b, they'd move down the page, and there'd be a current generated round there, that way.*

Here, the student has reasoned clearly in terms of particles in the bar, giving them a causal role in the existence of the current, and considering the effect of the magnetic field at each point in the bar. The student's use of this reasoning based on charged particles was confirmed in later questioning:

> *Interviewer: O.K., so you've already talked about electrons moving through the circuit, and what's the cause of the electrons moving?*
> *Student: Uh, the force [pause] because the bar is moving, therefore the electrons are moving and so they experience a force.*
> *Interviewer: So you say because the bar is moving, the electrons are moving in which direction?*
> *Student: They're moving with the same direction as the bar, but then they experience a force and then they move down the bar.*

In the above, there is a the clear causality running from electron motion to current, which contrasts with the approach of the less sophisticated students, who reasoned starting from the existence of the current. Rather than focussing on causes of the current, the next question looks at its effects.

<u>*Question 1 of interview 3, part (ix): Students' general summary of situation*</u>

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

Just as students had difficulty explaining the effects of the current in the question treated above, they had difficulty when asked to make a general statement about what was happening in this situation. While they raised some points about the situation, there was no strong underlying form to these points. Three students had no response for this question.

<u>Concrete symbolic responses</u>

All the students' responses to this question fell into the concrete symbolic mode. The six students who gave unistructural responses concentrated on the movement causing a current only, as in this response (s.17):

> *Interviewer: O.K., in general, what happens if you move a wire through a magnetic field?*
> *Student: In general [pause] uh, you get a flow of current.*

Interviewer: O.K., would it depend on anything else?
Student: Well, you've already told me I've got movement, so [pause] it depends on that.

In the above, there is a concentration on the single idea that movement of the wire causes current.

The six responses in the multistructural category had this idea of a current caused by movement, but also mentioned other concepts, such as velocity, field strength, direction and bar length. The student (s. 22) quoted below was an example of this multistructural category of response.

Interviewer: O.K., what happens in general if you move a wire through a magnetic field?
Student: ... You'd have a current flowing.
Interviewer: O.K., what does the effect depend on?
...
Student: Field strength and the velocity [pause] and also the length of the bar, I would think, yeah, I think it also depends on the length of the bar as well.

No students provided answers to this question which showed structure at a higher level than the multistructural level quoted above. None of them linked together these ideas of field strength, velocity and length in a coherent way, which would have been a relational response. It seemed that students were unable to make a complete summary of the situation when asked this general, non-directive question. This reflects their lack of overview of the situation. In a case like the above, where the questions does not provide a structure for their responses, they were unable to generate a structure from their own knowledge.