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RESEARCH REPORT

Teaching Direct Current Theory Using a Field Model

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Principles of direct current have long been recognised in the literature as presenting difficulties for learners. Most of these difficulties have been reported in the context of the traditional electron flow model. In this paper, an alternative approach for high school students using a field model is explored. Findings from a range of short pilot trials using this approach are described. These preliminary findings indicate that the field model, as an alternative approach to teaching about direct current, may be more successful than the traditional electron flow model for students in high school.

Keywords: *Physics education; Alternative conception; Model-based learning; Electricity; Field theory*

Introduction

The formal teaching of electricity commonly begins when students are aged about 14. At this stage, students are usually required to understand aspects of elementary circuitry, including resistors in parallel, resistors in series, and Ohm's Law. In broad terms, the 'scientific view' presented to high school students has been that direct current is due to the flow of charged particles under the influence of a potential difference across the ends of a wire. This model generally requires students to have a rudimentary knowledge of atomic structure. The mental images associated with this model are reinforced by common analogies used by many teachers and in textbooks. Despite international attention to teaching the electron flow model, however, it is generally reported that students of all ages lack deep understanding.

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Worldwide research has shown that students often have alternative conceptions about the nature of electricity and its behaviour in simple circuits, and that these conceptions are difficult to change even after several years of high school and university tuition. Many authors have addressed the problems associated with the electron flow model, which include difficulties associated with terminology, mental models, and concepts of current and voltage. For example, mental models associated with electrical concepts were investigated by Borges and Gilbert (1999). Difficulties with sequential reasoning were identified by Closset (1983), Engelhardt and Beichner (2004), and Fredette and Lochhead (1980). Viard and Khantime-Langlois (2001) described problems with understanding resistance. Cohen, Eylon, and Ganiel (1983) investigated alternative conceptions, as did Dupin and Johsua (1987), Heller and Finley (1992), Osborne (1980), and Shipstone (1984). Problems with electrical language, especially addressing the concept of voltage, were discussed by Duit (1985), Millar and King (1993), and Psillos, Koumaras, and Tiberghien (1988). Eylon and Ganiel (1990) looked at macro- and micro-relationships in a circuit. Licht (1991) demonstrated the importance of tinkering; Steinberg (1985) designed a programme around capacitance as a primary concept and emphasised transient phenomena. A major overview of research in understanding electricity was provided by Duit, Jung, and von Rhöneck (1985), while Psillos (1998), and Mulhall, McKittrick, and Gunstone (2001) made eloquent pleas for change.

Other authors have addressed a variety of analogies which might improve understanding. These include the water model, the gravitational model, and the teeming crowds model (e.g. Dupin & Johsua, 1989; Gentner & Gentner, 1983; Kircher, 1985; Paatz, Ryder, Schwedes, & Scott, 2004; Schwedes, 1985). Stocklmayer and Treagust (1994, 1996) proposed that a field-based model might offer an alternative approach that addressed some of these difficulties. The ideas of all these researchers were influential in designing the teaching and learning sequence described in this paper.

Mulhall et al. (2001) present a comprehensive summary of the state of teaching of electricity and conclude that an important issue is the lack of clarity in intended learning outcomes. They ask:

- i. What range of models/analogies/metaphors is appropriate in the teaching/learning of electricity at different levels of education? This includes what justifications there are for each model and its use at a particular level;
- ii. What, in detail, we expect students to learn when we talk of “conceptual understanding” in electricity? (p. 583)

Duit and von Rhöneck (1998) identified three key concerns in the teaching of electricity. These are:

- (1) Current flow and energy flow have to be clearly differentiated from the very beginning
- (2) Current and voltage have to be differentiated from an early stage
- (3) It is necessary to guide students to a “system view” of the electric circuit (that is, when one thing changes, there are also changes at other points). (p. 8)

As may be seen from the authors listed above, the research into ways to teach direct current circuitry has been carried out over a long period and is continuing. It has become clear that most of the problems and misconceptions remain unresolved. In the past few years, however, a major programme using the field model has been introduced at tertiary level in the USA, led by Ruth Chabay and Bruce Sherwood (Chabay & Sherwood, 2006, 2007; Sherwood & Chabay, 2001). This programme has sought to introduce an intensive study of magnetic and electric fields into the first year of tertiary education.

The textbook which describes this teaching programme has now been adopted by many of the major engineering schools in the USA (Robert Beichner, personal communication, October 2007) and at first year level in my own university. In a promising study with American tertiary students, Thacker, Ganiel, and Boys (1999) showed that reasoning about transients in electric circuits was greatly enhanced by examining processes at the microscopic level as suggested by this text. It is therefore reasonable to suppose that the field model is now seen by many, at least at the tertiary level, as an alternative which is preferable to the electron flow model.

I explore ways to teach this model at a lower level, which I believe to be possible even with primary school students, though an extension to primary level is not developed further in this paper. I will describe some early work conducted over 10 years, at which time I found it difficult to get the field model accepted by science education researchers and practitioners as an alternative. In these early trials, the field model proved preferable in that it is more coherent and overtly deals with the many misconceptions about direct circuitry identified in the literature. It also addresses the concerns of Duit and von Rhöneck (1998) outlined above. I will also describe a recent trial with a mixed group of high school students completing a physics 'bridging course' to enable entry to university.

In terms of electrical content, this paper covers the range of 'expectations' found in many syllabuses for students in middle/high school and beyond: that is, an understanding of elementary circuitry enabling simple calculations for resistors in series and parallel, batteries in various configurations, and so on. This understanding is expected to transcend alternative conceptions such as those identified by Shipstone (1984) and others.

The Field-Based Model

The field model may, at first glance, appear a more difficult and less useful one than the electron flow model, but the proposition that it be used in high school electrical courses is based upon support for the field model amassed over several years (Borges & Gilbert, 1999; Chabay & Sherwood, 2006; Ding, Chabay, Sherwood, & Beichner, 2006; Engelhardt & Beichner, 2004; Farwig, 1985; Furio & Guisasola, 1998; Härtel, 1985; Stocklmayer & Treagust, 1994, 1996; Thacker et al., 1999).

The original field concept is due to Faraday, and was subsequently described mathematically by Maxwell. It was never, however, considered a useful way to think about circuits by textbook writers until very recently. Although used extensively in

magnetism and electrostatics, it has been ignored in elementary circuitry (Stockmayer & Treagust, 1994). The field model, based upon ideas about potential difference and holistic circuits, constitutes a very different approach from the current-based electron flow model. Recent investigations with tertiary students in the USA, mainly in engineering, have indicated that they have an enhanced ability to solve complex problems and retain fewer misconceptions when the field model is taught carefully and in micro-detail (e.g. Ding et al., 2005).

Changing the perceptions of what constitutes useful knowledge in electricity is a difficult and challenging task. The field model has not, however, previously been investigated at school level. This paper is the result of a challenge to show *how* this might be done in the classroom and to demonstrate that field ideas can be learned by younger students in a fruitful way.

Ideas Underpinning the Field Model

High school textbooks do not generally deal with field phenomena in circuits. This makes it difficult for teachers to synthesise useful information for themselves, let alone their students. Walz (1985) described the nature of fields that accompany currents in a mathematical analysis which is of great value in understanding the nature of electric fields in simple circuits. The subject is, in his own words, 'not usually treated in either textbooks or even at university level' (p. 404). He begins his discussion by explaining that there is, within a current-carrying wire, a 'homogeneous coaxial field'. The field-generating charges are located at the surface of the wire.

Härtel (1985) also focused on this important point. He stated that there is a conceptual difficulty with understanding why there may be a considerable potential drop across a resistor, but little measurable drop along a conducting wire. There is a gradient in the charge distribution, which results in a different field for the wire from that of the resistor. He said:

It is an astonishing fact that physics education has overlooked a rather simple explanation for this question: the existence of surface charges, accompanying any current flow within a conductor. The existence of these surface charges are described in some textbooks and in some articles. In most cases, however, they are not mentioned. The reason for this lack of attention to an existing physical phenomenon may be found in the fact that these surface charges are rather small and not normally detectable. (p. 357)

Sherwood and Chabay used Härtel's (1985) work to inspire a college-level teaching sequence based on similar principles (Chabay & Sherwood, 2007). In this text, these authors reject the electron flow model in these terms:

One might argue that in a circuit each mobile electron makes an electric field that affects the mobile electron to the left of it, ("pushing" on its neighbor), thereby causing current to flow. Given our description of the mobile-electron sea in a metal, what is wrong with this analysis?

As we have stated previously, there can be no excess charge in a conductor, so the number density of mobile electrons inside a metal wire must equal the number density

of positive atomic cores—the inside of the wire is electrically neutral ... the repulsion of a mobile electron on the left by a mobile electron on the right is cancelled by the attraction of a neighboring positive core, so the total force on a mobile electron due to the other mobile electrons and the positive cores is zero. The result is that the mobile electron-sea behaves rather like an ideal gas, in which none of the particles interact with other particles. Electrons cannot continually push each other through the wire like peas pushed through a tube from one end of the tube. Rather, it must be other charges somewhere outside the wire that make an electric field throughout the wire that continually drives the electron current. (p. 627)

These authors saw that the field approach provided an opportunity to link electrostatics and circuits and found that ‘surface charge analysis can be made teachable and learnable and that it provides a strong sense of mechanism’ (p. 13). The result is their textbook that deals with simple circuits entirely from this perspective. The ideas of charge and field distribution are nevertheless quite complex. When considering a simple circuit with one resistor, for example:

The electric field in the resistor must be quite a lot larger than the electric field in the thick wires... In the steady state the surface charge varies only a little along the thick wires, producing a small electric field. Along the resistor there is a big variation from + at one end to – at the other... This makes a large drift speed in the resistor. (Chabay & Sherwood, 2007, pp. 639–640)

It is not suggested that these more complex ideas be included overtly in middle/high school teaching about circuits. Nevertheless, they form the foundation for the field model in dynamic electricity and, at a later stage, can be addressed. Poon (1986) proposed that ‘perhaps the greatest reward in introducing the field description is that it enables us to deal properly with the idea of potential energy’ (p. 307). This is the core of the argument for teaching all students about fields.

Fields in electrostatics have received more attention in the literature, but the research is only relevant to this paper where the issues discussed relate to dynamic fields also. Recently, for example, Pocovi and Finley (2003) identified some problems with the way that electrostatic fields are presented in college physics texts. They urge teachers to explain that ‘the field is *fundamental* in the description of the electrostatic phenomena because once the field equations are known the electric system is completely described’ (p. 394, my italics). This point is subtle but important for a college-level understanding of modern notions of fields. It is thoroughly addressed in the text by Chabay and Sherwood (2007). Further, the transition from electrostatics to direct current circuitry and, indeed, to alternating currents is then smooth, uncontroversial, and coherent.

I mention these recent findings to illustrate two important points in this paper. First, fields are critical to students’ understanding of both electrostatics and electrodynamics at a tertiary level, and second, they are poorly understood, even by teachers at this level. It seems desirable to try to introduce fields earlier so that the overarching ideas are well established before complex problems are presented.

With all these issues in mind, therefore, three short pilot classroom trials of a field-based model were conducted. I must emphasise, however, that the trials were not

intended to do more than to indicate the *feasibility* of teaching simple circuitry using a field-based model. To implement universal field-based teaching in high schools requires curriculum change, which means that the theory needs to be accepted by curriculum designers as a valid way to teach this topic. This requires resources to be developed and professional development for teachers to be implemented. This is a situation which is difficult to resolve, but one may hope that the increasing evidence will, in time, prove convincing. Testing the field-based method with high school students therefore meant identifying teachers who were prepared to take a risk, and this meant that the trials were essentially opportunistic.

Field Ideas in the Classroom

If field ideas are to be used in teaching, the aim must be to encourage the students to regard circuits as systems in which electric fields are established at speeds close to the speed of light (in the trials, I drew an analogy with a communication 'signal' and information). This is the primary idea. The existence of electromagnetic fields, with associated potential differences around the circuit, is the most important principle to establish, with current as a consequence of the field being a secondary idea. (Surface charges, which are responsible for the field, need not be emphasised to middle school students.) The fields transfer energy to the load, which then performs some useful function. The load also assists in determining the characteristics of the overall field so that the field is determined not just by the source but also of the circuit components. Any local changes in any component will affect the whole field and hence the behaviour of the circuit. The field model therefore addresses all three important points mentioned by Duit and von Rhöneck (1998), above.

These ideas depend upon students' understanding something of the nature of a force field. It is important to recognise that they will have very limited experience of fields and, perhaps, of forces. The whole model has to be built upon very carefully with close attention to their previous alternative ideas, including the use of language.

The teaching sequence was broadly identical for both groups in the first two of the three trials following a common pattern:

- (1) The first step, based upon the literature concerning constructivism, misconceptions, and analogies, was to ask the group about their ideas of a field in ordinary life. 'Sports fields' were chosen to sketch an extended analogy with fields in physics.
- (2) Parallels with gravitation, magnetism, and static electricity were then drawn, with constant emphasis on potential difference, force, work, and energy. The importance of *change* in a field was elaborated.
- (3) Fields in dynamic circuits were introduced, focusing on potential difference and energy. Time was also spent physically demonstrating that any change in a circuit resulted in an instant change to all other characteristics.
- (4) Resistance and current were explained and explored, together with series and parallel circuits.

Step 1: Fields in ordinary life

In forming an analogy with a hockey or soccer field, students were asked how they would identify whether a game being played on a field was hockey or soccer (football). At this point, the underlying agenda was to establish that behaviour on a playing field depends on the nature of the field itself (in this case, the nature of the game that is played), and that the 'players' are themselves able to respond to the field (the game). So you have to be suitably equipped to play hockey or football, and the wrong equipment means that you cannot play the game. Part of this agenda was also to establish very strongly that movement of one 'player' affects all other players almost instantaneously. This idea would later be fundamental to addressing misconceptions such as the idea that current becomes weaker as you go round a circuit (Shipstone, 1984 and others). Changing any component was seen to affect the entire circuit. It also addressed the problems of the model of mechanical 'push' due to Newtonian analogies such as the teeming crowds analogy, the water analogy, or the train on a track collecting and depositing energy. This problem was elaborated by Chabay and Sherwood (2007), as discussed above. Useful ideas are summarised in Table 1, Column 1.

A second important idea was the notion of 'having potential'. This is a common expression, and it was pointed out to students that implicit in this everyday phrase is the idea that one has the possibility of moving on, to some other position. There is therefore a beginning point and an end point—a difference. In addition, it takes *work* to move through this difference to a higher potential. These ideas were then extended to force fields (Table 1, Column 2).

Step 2(a): Extending these ideas to gravitational fields

The first step in moving to fields in physics was to relate the ideas described in Table 1, Column 1, to gravitational fields. Students carried out a range of exploratory experiments in which they examined falling objects and made analogical comparisons to their previous ideas about sporting fields. They identified and sketched force lines, talked about potential differences and work and sketched the direction of the field. Given that the students had had some previous experience of gravitational experiments and observations, this was a short but comfortable move into the use of terms like 'potential difference'. The idea that a gravitational field has its origins in mass and that a 'field detector' must also be a mass was discussed, as was the idea that if a body (a 'player') in a gravitational field is free to move, it will move. The notion of forces always existing as mutual force pairs was important to emphasise the importance of Newton's Third Law in understanding the nature of a gravitational field and any changes resulting from the movement of objects within the field.

Step 2(b): Extending these ideas to magnetic fields

In similar fashion, students observed, sketched, and discussed magnetic field lines and the direction of the field at any point. Potential differences were again

Table 1. The field model

The field and the players: initial ideas	Extending the field model to gravitational, magnetic, and electrostatic fields. Potential and potential difference
You have to have a field ‘detector’ (a player affected by the field) to know the field exists—an empty field (with no players) tells you nothing.	A force field has the <i>potential</i> to move detectors—objects affected by the field. At any point, a force line (a field line) gives the direction of the field. The detector will experience a force in this direction. ^a
If you haven’t got the right equipment you can’t play the game: this translates to having <i>mass</i> to ‘play’ gravity, having <i>magnetic</i> characteristics to ‘play’ magnetism, and having <i>charge</i> to ‘play’ electricity.	If a detector has the potential to move, it will move if free to do so.
The players obey the rules of the game.	A potential <i>difference</i> must exist between two different points on a force line.
A field has ‘lines of action’ which help to explain how players move: each player knows where to go next as other players move. The lines are imaginary.	To move objects in a field requires work to be done—the result is a change in potential energy.
If one player moves position, all the players move in response.	The detectors (test objects) in a force field exert a force themselves (that is, they are part of a force pair) and <i>contribute</i> to the overall field (unless of course the detector is a device such as a ‘point mass’—which can easily be explained should the topic arise).
Information is generally transmitted between players at speeds approaching the speed of light.	

Note. There are many differences between a sporting field and a force field: these include the nature of field boundaries, the importance of the ball, and so on, but the analogy proved useful in assisting reasoning about force fields despite the obvious differences. These differences were mentioned in accordance with ideal analogy use elucidated by Treagust (1993).
^aNote that the detector will not necessarily move in this direction. In the case of a projectile, for example, the force line is vertically downwards and the object experiences a force in this direction but moves in a parabolic arc.

emphasised. For example, moving one magnet with respect to another enabled the force to be ‘felt’ by the student as work was done. Bar magnets were used to explore a field due to one, two, and many magnets, pointing out that in every case there was just one overall field which also included the earth, and that any change to the position of the magnets changed the nature of the field. The idea was discussed that if a magnetic field is observed to affect ‘detectors’—in this case iron filings or compasses—then the detectors themselves must have magnetic characteristics. They will move if free to do so. The ‘lines’ indicated by iron filings are arbitrary but useful in sketching the overall pattern of the field.

Step 2(c): Extending these ideas to electrostatic fields

While magnetism and magnetic field lines were also fairly familiar to students, the extension of these ideas to electrostatics was not so familiar. Thinking about field lines and field direction between, say, a charged balloon and a hair, glass and silk, or two charged pith balls was not something previously encountered. Demonstrations of electrostatic fields on the overhead projector helped in this regard (see, e.g., University of Melbourne, 2007). The continued use of terms like force, potential, work, and energy in Steps 2(a)–2(c) meant that students were able to see an overall pattern of ideas and language in these three areas. Students were also asked to explain phenomena such as plastic bags sticking together or polished mirrors attracting dust, in simple field terms. Work was discussed in terms of the transfer of charge such as in a van de Graaff generator. Part 2 of the unit is summarised in Table 2.

Step 3: Fields in circuits

After careful work in establishing these common principles in gravitational, magnetic, and electrostatic fields, students were introduced to circuitry. When introducing the field idea in electric circuits, ideas about current were entirely secondary to the importance of potential difference, now called voltage, and to the load as a site of energy transformation. A major step in the argument was that the battery provides a source of potential difference which governs the field around the circuit. The idea that the conducting wires simply provide a guiding mechanism for the field to be applied across the load, in order to achieve useful outcomes, took time and care to establish. The load is in effect a sink, the battery is a source.

The almost instantaneous establishment of the field along the wire (the ‘message’) and the subsequent behaviour of the electrons in the wire was an important

Table 2. Summary of the introductory steps to establish the nature of fields in physics

Type of field	Origin of field	‘Players’	Issues discussed
Gravitational	Presence of masses	Masses	Potential/potential difference, lines of force, work Potential and potential difference were discussed—some previous knowledge. Lines of force were derived from experience and experiment. Work was associated with moving masses in the field.
Magnetic	Presence of magnetised objects	Magnetised objects	Potential and potential difference were discussed as an extension of gravitational field ideas. Lines of force were observed by experiment and discussed. Work was associated with moving magnetised objects in the field.
Electrostatic	Presence of electrostatically charged objects	Electrostatically charged objects	Potential and potential difference were discussed as an extension of previous field ideas. Lines of force were observed and deduced by experiment and demonstration. Work was associated with moving charged objects in the field.

discussion, which enabled ready understanding of the global effect of changing components in the circuit. Students explored the effect of changing the components in a simple series circuit and discussed their observations in field terms. Higher level students were given an explanation of *why* the energy is transformed in the resistor using Chabay and Sherwood's (2007) explanation that electrons moving through a resistor must be accelerated (p. 639). Lower level students simply measured this potential difference by experiment. (It is, however, quite acceptable at any level to point out that the field in the conducting wires need not be large in order to maintain a constant-speed of electron movement in the wires.) The effect of the accelerating electrons within the resistor is, in many cases, to heat the metal.

Students also discussed the idea that the field across an open switch is normally insufficiently strong to allow completion of the circuit by producing breakdown of the air.

Step 4: Circuit relationships

Relationships between resistors in series circuits and the voltages across them were deduced through reasoning about total and partial potential differences in different parts of the circuit. In summary, at this point the following ideas were well established:

- *Potential difference* is the all important factor in setting up the field that moves the players—*voltage* is what governs the energy transformations in the circuit.
- Current is the result of the action of the field on the 'player'—that is because the electron is free to move, it will move.
- Everything in the circuit determines the nature of the field. If one circuit element changes, everything has to change. A new field must be established.
- Moving the 'players' requires energy. In the case of a resistor, this means the field has to do work on the electrons to move them through the resistor.

After tinkering and exploration with series circuits, students were introduced to parallel circuits. This step was not particularly problematic because students were highly voltage-driven rather than current-driven. It was straightforward, therefore, to understand that the potential difference was the same across parallel branches. Household wiring was an important topic in the first trial.

The Pilot Trials

The three student groups selected for the trials were quite different and each group had features which made them particularly challenging. The groups are described in Table 3.

The potential for bias, because of my own involvement, is acknowledged. Questionnaires and interviews provided an additional source of triangulatory data to classroom observations and students' workbooks.

Table 3. Pilot trial groups

Description of group	Number in group		Length of trial
	Male	Female	
First trial			
Year 9 (14-year-olds) in a private Australian girls' school	0	25	5 weeks (25 lessons)
Little or no experience in electricity			
Middle ability group, prescribed syllabus			
Taught by the regular teacher (see text)			
Second trial			
Year 11 (16-year-olds) in first year of upper secondary physics, Australian public (government) school	10	8	3½ weeks (11 lessons)
Previous Year 9 unit on electricity			
Middle ability group, prescribed syllabus			
Taught by the author with help from the regular teacher (see text)			
Third Trial			
Physics 'bridging course' for university entry into an introductory physics course. Conducted through an intermediary college			4 weeks (12 lectures and 12 tutorials)
Group A (just completed final high school year, no previous senior high school physics)	9	3	
Group B (second language English, just completed upper high school physics)	7	1	
One introductory lecture from the author, plus an optional remedial session. Otherwise taught by the regular teacher (see text)			

The First Trial

The class of 14-year-old girls was timetabled for a five-week period of instruction in electricity at the beginning of their second year in high school. Preparation for this had consisted of some preliminary work on forces and matter in the previous year, but no formal teaching in electricity. The 25 students in this class had been streamed at the end of the previous year into the middle group of three achievement-based classes. The teacher concerned ('Patrick') volunteered to trial the field idea, a risky procedure for him because there was an expectation that his class would receive identical content to the 'top class' despite their disparate achievement levels. The pilot trial thus had to be designed around a set of objectives that were quite demanding for this level of student.

Patrick had no previous knowledge of the field-based approach. He outlined his own images of electricity in an initial interview:

- Patrick: I think I've definitely got an 'electrons moving through a wire' sort of idea.
- Interviewer: What do the electrons look like?

Patrick: They look like little round things that go through there and make their way through ... I've also got a bit of a sort of valence idea, of them sort of being transferred through atoms through the outer shells.

Patrick's own images were therefore very much in line with other teachers of physics (Stocklmayer & Treagust, 1996). Teaching a field model was a very different approach for him to take and required considerable prior discussion with the author. Classroom notes, prepared jointly with the author, were designed as a student resource.

Whatever teaching model is used, it should also incorporate strategies that other researchers have identified as important in the learning of simple circuitry for all students. These may be summarised as a tinkering hands-on approach (e.g. McDermott & van Zee, 1985), a constructivist approach (e.g. Arnold & Millar, 1988), and attention to difficulties with language (e.g. Duit, 1985). In general, therefore, as well as the field model, these previously recommended strategies were incorporated as much as possible as well as emphasis on voltage and energy and the suitable use of analogies. Practical work was frequent and largely exploratory. No fluid language was used anywhere, either in text or by Patrick, except for the word 'current' later in the unit.

Throughout the trial, I attended lessons as an observer, making recordings and field notes. Interviews were conducted with teacher and students. During practical sessions, I moved around the classroom making observations and, on occasion, talking with the students. The students were fully apprised of the reasons for the observations and recordings. Only the results from the trial that relate directly to aspects of the field model in circuits will be reported here. Important issues for the teacher will be addressed in a following paper.

The preliminary questionnaire. Before commencing lessons in electricity, students were given a preliminary written questionnaire and some were interviewed. Questions were mainly about imagery and language: no circuits were included because the students had had no previous tuition in this aspect. Most students claimed, however, to be familiar with the terms 'current' and 'volt', a result which, at first glance, may seem a fruitful starting point for an introductory electrical unit. In interviews, it became clear that these students actually had little understanding of these quantities from the perspective of acceptable scientific explanation, and were confused about the scientific meaning of the terms:

Volts are—like—carried through the electricity and in the power lines there's a certain amount of volts I'm not really sure.

Current—is that when it's just carried along?

Current is like lots of electricity—bits—all going through in a wiggly line.

I included a question which I had previously found useful in eliciting electrical imagery from tertiary students: 'How would you explain that the wires in a toaster get hot, but the wires leading to the toaster do not get hot?' Some interesting ideas

included: 'there are many volts inside this tube and when it hits the volts from the toaster it heats up' (the clashing currents idea?); 'electricity is pumped into the toaster'; 'the wires don't go any further'; 'the electricity only comes to the toaster, heating it and doesn't go the other way'. Overall, the preliminary test indicated that these students were not very different in their understanding from others described in the literature.

Changing ideas: intermediate and post-tests. The first part of the unit followed the lines described above. In an early formal test, students volunteered the following comparisons between a sporting field and a field in physics:

Both fields have concentrated areas which have more force lines or play.
If any one thing in the field changes, the whole field changes.
Field detectors are arranged in a field like players are arranged on the field.
They both have field patterns.

From these responses, students' ideas about fields were clearly embryonic, but the sporting field analogy did appear to be a useful introduction to the field model.

Formal aspects of voltage were introduced well in advance of formal aspects of current, as recommended by Härtel's (1985) work and by Sherwood and Chabay (2001). In the mid-topic test, a question about what governs movement of charge elicited 22 responses of the type: 'there will be no movement unless there is a potential difference' or 'a potential difference is needed, measured in volts'. Answers such as these from the majority of students did at least indicate that, for this group, the term 'potential difference' had the same meaning as was intended when designing the teaching sequence.

In a post-test, I asked a question which would be repeated in subsequent trials (Figure 1). This question is a regular diagnostic tool for Shipstone's (1984) models of current.

In this case, all the 23 respondents answered correctly that the bulbs would all go out. Students were asked to explain their answers 'using your knowledge of electric fields': the following are examples of the explanations:

If you change the pattern or anything in a field, the whole field changes.

The wires have been cut from the source of energy and it causes the force lines to weaken and the electricity can't jump across to the wire as it's not strong enough.

You are disturbing and changing the whole field: the field would be broken.

There is no potential difference across the bulbs because the field would have changed and the force lines become too weak to give a potential difference.

You are breaking the electrical loop.

It seemed probable that at this point, the students were reasoning in field terms and their field ideas appeared to be meaningful, even if rudimentary. The term 'broken' is technically incorrect but likely attributable to imprecise language during

- If Bulb 2 is removed from its socket, what happens to the brightness of the other bulbs?
- If Bulb 5 is removed from its socket, what happens to the brightness of the other bulbs?

Figure 1. Change in a circuit. Adapted from Shipstone (1984, p. 186)

the teaching. Note that the 'loop' explanation results from strong emphasis on the holistic nature of the circuit and the fact that it constitutes a closed loop around which the field is established.

A similar question about three loops in parallel (Figure 2) resulted in 22 students saying that the remaining bulbs would have the same brightness as before. 'A parallel

What happens to the brightness of Bulb 2 when Bulb 1 is removed

Bulb becomes:

- Brighter** ☐
- Stays the same** ☐
- Less bright** ☐

Figure 2. Question about a parallel circuit. Adapted from McDermott and Van Zee (1985, p. 40)

circuit distributes the electricity through all of them making the brightness in two bulbs the same as one’.

The students seemed to have had little trouble with the relationships between potential difference, current, and resistance, and regarded Ohm’s Law as a simple expression of these relationships. For example, when comparing household- and battery-driven circuits, Lara said, ‘the potential difference in the battery is usually very low or very small and therefore it’s not a very powerful electric current’. By this stage, however, some students were consulting textbooks and were recording other ideas in their workbooks. Samantha wrote that current is ‘a flow of charge’, an ampere is a ‘measure of current flow’, and resistance ‘reduces the current flow around the circuit’. Despite the best efforts of Patrick, therefore, students were obtaining ‘flowing’ images from external sources which, in some cases, led to confusion between the field and electron flow models. It was evident from this trial that, having established the idea of potential difference, aspects of current need also to be explicitly and carefully addressed in field terms. Current is a consequence of the field and is a movement of each individual electron in response to the field, not a sequential one. Traditional textbooks are therefore likely to be problematic.

In summary, students in this class progressed in their understanding of potential difference and the way in which it controls series and parallel circuits. The students’ language about potential difference was closer to the accepted scientific language. In interviews, it was clear that students were in the process of revising their earlier impressions in the light of new knowledge. Their new images were more energy based than before, relating quite strongly to what electricity could do. For example, in the pre-test, Ann had likened electricity to a fire or a dangerous animal. She now said that it was ‘a controlled resource, something that you can tap into’. Samantha thought the best simile was ‘a source of energy’.

In general, the first trial indicated that the field model could be a genuine alternative to the electron flow model. The language used by the students throughout the unit was voltage based and generally had few connotations of fluid imagery.

The Second Trial

The class of students participating in the second trial consisted of 10 boys and 8 girls, all about 16 years old. The choice of a higher level class for the second trial was to test the field ideas with students who had already had some experience of electricity. In this case, I taught the class in a guest capacity.

The Year 11 course in Australia is the first year of upper school specialisation. Once again, this class was a second-level achieving group, taught in parallel with a higher achieving class. The content had to fulfil a set of prescribed traditional objectives, which would dictate both the pattern of teaching and the final examination. While this was challenging for the field model, it was nevertheless an interesting and exacting way to trial its feasibility.

In following the prescribed syllabus, the materials could still be designed around the same introductory framework as the previous trial. Fields could be introduced through analogies, as before.

The students had elected to study physics and all had completed a preliminary electricity unit in Year 9. In addition, a few of the boys had completed an electronics unit in Year 10, which, it was thought, would give them an advantage from the point of view of tinkering experience. The students were of mixed achievement and motivation. It was not expected that all of the class would continue to Year 12 physics. The regular teacher, 'Toby', was a young, first-year postgraduate who was interested in innovative teaching techniques in physics and it was agreed that he should observe all teaching sessions and comment wherever possible. He held the traditional physics teacher's electron flow model, but was looking forward to challenging it.

At the outset, Toby and I explained that the purpose of the trial was to assist in the way that students thought about electricity. Since they had already had some tuition in Year 9, very similar to the syllabus for students in the first trial, the purpose of this trial was stated to be a provision of an alternative approach that they might prefer to use, depending on whether it appealed to them. Throughout the unit, I kept a diary of comments after each lesson. Toby was consulted regularly about his impressions. Students' work was monitored and the final examination provided some indication of overall achievement.

The preliminary questionnaire. The questionnaire administered to this group had more emphasis upon circuitry because the students had studied electricity before. It consisted of seven questions, three of which are discussed here: a question about electrical terms and units, the toaster question as before, and a diagnostic circuit question.

When the students were asked about their understanding of various electrical terms, they showed that there was a considerable degree of confusion. Many students avoided answering parts of this question. 'Electric current' was described by most of the class in terms of electron flow, indicating that this model was well established by this stage. Many of these were conventional answers that would be judged acceptable by most teachers. For example, electric current was described as 'electricity going from one place to another; a current passed through wires—transfer of electrons, electricity moving together continuously through conductors, the flow of electricity'. Ideas about voltage, however, were much less scientific. 'Voltage' was 'the amount of electricity passing through something; a number of volts in a charge, amount of energy or power, amount of electricity flow, measurement of current'.

Similar difficulties were experienced when explaining resistance, with seven in the class using phrases about 'resisting electricity' such as 'resistance is how much the wire resists the electricity passing through it'. Two students said, 'an opposing force' and two thought it slowed the current down.

The question about the wires to the toaster evoked some answers that illustrated similar confusion:

The leads are insulated by plastic or some other insulating material and so don't get hot, but the wires are uninsulated bare metal and are designed to get hot.

The wires in the toaster are exposed to both air and electricity while the lead is not.

It was clear from this questionnaire that the class as a whole did not have a scientific conception of electricity and electrical terms. The third question related to the five-bulb circuit used in the first trial (Figure 1). Shipstone (1984) described four models relating to student ideas about the behaviour of such a circuit. Model 1 is the very old 'clashing currents' model, in which two currents emerge from the battery in opposite directions, colliding in the load. Model 2 embodies the idea that current is used up sequentially around a circuit, getting weaker as it goes. Model 3 also includes the notion that current is consumed, but the current is shared equally between components. Model 4 is the accepted 'scientific model'. It was evident that Models 2 and 3 were dominant in this class (Table 4).

This classification of the students was based on only one question, yet the pattern of explanations was so typical of these models that the categorisation of responses was unambiguous. The gender difference was very marked, with the girls notably less successful than the boys in their responses to all questions: further discussion of the gender effect will be deferred to a subsequent paper.

The preliminary questionnaire indicated that, in many ways, this second group of students initially shared the same perceptions of electricity as the Year 9 group. Their ideas appeared to correspond closely with many of the alternative conceptions identified by previous research. In general, therefore, these students had a level of understanding of electricity that indicated that they had retained little of their Year 9 instruction (which itself may have been problematic) although some of their notions of current were useful and facilitated subsequent understanding of the effect of the field.

Changing ideas: intermediate and post-tests. I began this unit in a similar way to the Year 9 trial, through analogies with sporting fields. The content followed a similar pattern throughout, with emphasis on field-based reasoning and practical experiences. The strong mathematical emphasis being given to the parallel class represented a constraint for these students, but they nevertheless completed the prescribed content in the allocated time.

Table 4. Diagnostic question about circuits, second trial ($n = 18$)

Response	Males	Females
All go out (Shipstone's Model 4: the scientific model)	5	0
Some sense of sharing (Model 3: current shared, gets used up)	4	1
Brightness increases (unspecified)	0	1
Brightness increases after Bulb 2, or stays the same	1	6
Bulb 5 stays the same, it's the last in the line (Model 2: current gets weaker round the circuit)		

Table 5. Final question about circuits: post-test, second trial

Response	Males	Females	Gain from pre-test
All go out (Shipstone's Model 4: the scientific model)	9	5	+4M, 5F
Some sense of sharing (Model 3: current shared, gets used up)	1	2	+1M, 2F (all previously Model 2)
Brightness increases after Bulb 2, Bulb 5 all will go out (Model 2: current gets weaker round the circuit)	0	1 ^a	

^aAll but one student assumed the same behaviour for Bulbs 2 and 5. This one exception stated in Part 1 that the bulbs would get brighter, but that all would go out for Bulb 5 because the circuit has been cut. Her modelling is therefore difficult to classify but, erring on the conservative side, she has been classified overall as Model 2.

In a post-test, the five-bulb question from the preliminary questionnaire was included once more and responses were much improved. The level of understanding and the sophistication of the language were high. Their answers were now much more on target than before. Results for this question are shown in Table 5. A summary of these students' modelling modes before and after instruction is also shown in Table 5.

Explanations given by these students included:

The bulbs all go out because the field is disrupted and everything stops.

All the lights go out, since the circuit is in series, the circuit is cut, that is, the signal is cut so the electricity doesn't flow. The electric field isn't strong enough to pass a current.

The language used by the students in their answers, which in almost every case was more detailed and reasoned than before, indicates that this classification is probably correct. For example, Jane had previously answered in Model 2 mode as follows:

- (a) (If Bulb 2 is removed from its socket) The Bulbs 3–5 will become brighter because there is more energy left for them.
- (b) (If Bulb 5 is removed from its socket) Nothing, because it is the last in line and doesn't affect the rest.

During a practical session, Jane began to question her model, saying 'it gets weaker as it goes around—doesn't it?' This idea was debated and she appeared to accept the rationale of an energy 'signal' with information about the field being transmitted around the whole circuit. Her final response in the post-test was:

The other bulbs will all go out because in a series circuit if one goes out they all do. The same will happen. The connection is broken therefore the information will not be transferred around the WHOLE circuit so none of it will work.

This answer paraphrases the discussion at the time of the practical session and it could be that this is a learned response. It was echoed, however, by other students:

- (a) The bulbs all go out because the signal being transmitted through the circuit is broken, and so the field is disrupted and everything stops. (Michelle)
- (b) All the lights go out. Since the circuit is in series the signal is cut so electricity doesn't flow. The electric field isn't strong enough to pass a current. (Sam)

It was clear that the students now had a much better understanding of the overall nature of a circuit and of the function of a switch, an ammeter, and a voltmeter. They had some sense that the purpose of a circuit was to provide useful energy to the load. My notes from this section of the course state:

Today we did the series and parallel circuit practical. When they found the current to be the same around a series circuit they said they weren't surprised. (Hooray!!). They had no trouble with connecting the voltmeter across the loads either The parallel circuit was done in a bit of a rush (end of the lesson approaching) but the girls' group did it quite well They were quite happy that the voltage was the same across all—when I said “the field is the same around each branch” Mary said “Oh yes, of course it is ...” Encouraging!

Ohm's Law Practical. Brilliant, they did it in double quick time. Everyone set the whole thing up correctly at high speed and without any errors. No one put the voltmeter in series. Everybody was really happy today including me. I feel encouraged with their thoughtful setting up today. They were extremely confident although I did check all circuits.

Results for these students were therefore very positive. The field theory seemed to have provided them with an alternative way of thinking about electricity that had a notable effect upon the confused ideas of many students. This group, like the Year 9 students, began to use the terms ‘potential difference’ and ‘voltage’ casually and in a sensible way. They asked many questions about parallel circuits and were able to apply field ideas to explain their observations. Judging from their language, this progress seemed to be founded on voltage-oriented reasoning, with an appreciation of the almost instantaneous transmission of field information around a complete circuit and an understanding of the importance of a holistic view. These are important aspects of the field model.

The questions in the final examination, set by the senior teacher of the ‘top class’, consisted of traditional multiple choice and mathematical problem sections, together with Ohm's Law calculations of a fairly elementary nature. One question, however, was very similar to the five light bulbs one. In this question, all but one member of the trial class answered correctly, many using field-based explanations similar to those they had given before. Results from the examination were, from the students' and Toby's perspective, positive: he said that eight students had ‘lifted their grades’ from Semester 1, which the students found reassuring. Toby added that, overall, they had performed better than expected. The field model was not really tested directly in the shared examination, but it may be hoped that it helped them to achieve this improved result.

The Third Trial

The class of students participating in the third trial (see Table 3) consisted of a mixed group, both in character and in prior experience. The prescribed content of

the bridging course in physics, conducted through an intermediary college, was at a higher level than those of the first two trials, including simple circuitry, alternating currents, and electromagnetism. This course was delivered through university style lectures and practicals. There were two kinds of student in this course: the first group (Group A) consisted of those who would require some background physics during their first university year but had only middle/high school science. These had English as their first language. The second group (Group B) consisted of international students who had little English but had studied physics in school—they attended the class to gain experience of English in a scientific context before entering university. Group B students were familiar with all the formulae required for the course and were accustomed to reasoning from a mathematical perspective.

Clearly this dichotomy presented a challenge for Roland, a new physics lecturer whose first degree was in electrical engineering. After considerable discussion, he agreed to a small trial of the field model, starting with an introductory lecture from me to start the group on the idea of fields through the sporting field analogy. A pre- and post-lecture questionnaire was administered. After that point, I had no further classroom contact.

The preliminary questionnaire. Before the lecture, the students were given a diagnostic questionnaire consisting of three questions drawn from the literature. The first question concerned simple circuits (Figure 3).

Below you see two circuits. All bulbs are identical.
Compare the current at P with the current at Q.

The current at P is:

- More than the current at Q ☐
- The same as the current at Q ☐
- Less than the current at Q ☐

Figure 3. Question 1: third trial. Current in two simple circuits. Adapted from McDermott and van Zee (1985, p. 40)

The difference in these groups was immediately obvious. Group A was almost equally divided between 'more' and 'the same', while students in Group B, who were used to reasoning from the Ohm's Law relationship, almost all answered correctly.

The second question concerned the same five-bulb circuit discussed earlier (see Figure 1). Four of the 12 in Group A and one of the eight in Group B answered correctly. Three from Group A and five from Group B thought the brightness of the remaining bulbs would increase. Group B students generally used a formula to justify their conclusion. Reasoning was often confused:

Student 1A:

- (a) The brightness of the other bulbs after Bulb 2, that is, Bulbs 3–5 will increase. This is because the total potential difference, V , is divided among the five bulbs. Thus, if Bulb 2 is removed, there is more potential difference at Bulbs 3, 4, and 5.
- (b) The brightness of the other bulbs does not change. They already have 'consumed' a fixed amount of potential difference prior to Bulb 5 in the circuit.

Student 1B:

- (a) They get brighter because there is more current passing through the light bulbs without the extra light but will increase because the consumption of the current decreased.
- (b) No bulbs, no brightness: the electricity current would keep moving without any consumption.

Question 3 concerned parallel circuits (see Figure 2). Once again, few answered correctly. Six of Group A and three of Group B thought the brightness would increase. Two in each group thought it would become less bright. For this question, Group B students generally tried once more to use a formula, but in this case it failed them. In the case of incorrect answers, most either gave no explanation or stated a formula of some sort.

The general conclusion to be drawn about Group A in this class is that their answers were typical of previously recorded groups in the literature. Group B, who took refuge in formulae, were harder to classify, but the responses to Question 3 raised some doubts about the validity of their reasoning as opposed to rote application of a formula. It was of some interest, therefore, to examine the outcomes of a second test given after the lecture on fields. The five-bulb circuit was demonstrated physically in the lecture, as were the parallel connections of Question 3. Because these two questions were no longer going to depend on understanding but could be answered from memory, two further questions were added to provide new opportunities for explanation.

Changing ideas: intermediate and post-tests. The nature of the course meant that the only intermediate test that could be carried out took place immediately following the lecture on fields. In this test, students were asked not to use a formula in their explanations. In the lecture, potential difference, voltage, energy, and work were stressed, but the voltage/current and current/resistance relationships were not discussed. Question 1, which addressed the effect on current of changing the number of

resistors, was, therefore, not expected to show any change in the post-test and this proved to be the case. For Question 2, interestingly, two Group B students still maintained that the brightness would increase and used a formula to justify this, despite a physical demonstration of the effect. It has often been observed that students frequently see exactly what they expect to see! The remainder of Group B and all of Group A gave a correct answer, with 12 students using a field-based explanation such as:

They go out because there is an air gap in the field. The other bulbs will die out because a part of the series circuit has been removed thus disrupting the circuit and the field surrounding it.

All other bulbs cannot light up. The electric field has been changed such that the electrons now cannot flow across the circuit.

For Question 3, only one student did not give the correct response. Typical acceptable answers were:

Because the bulbs are connected in parallel they all have the same voltage of the battery regardless of the number of them.

The energy field is still the same regardless of how many circuits are connected. The only thing that changes is the amount of energy being transferred from the battery (potential) to heat/light.

A better test, however, was provided by the last two questions (Figures 4 and 5). Question 4 indicated positive conceptual changes, especially for Group A, but a minority of Group B students still attempted to reason from a formulaic perspective. All students in Group A ranked the brightnesses correctly in the second part of this question.

Results from Question 5 (Figure 5) indicated positive change, especially for Group A. 'Correct' explanations were those that were acceptable in both sections. Such explanations included for Part 1:

A and B have the same terminal potential difference as C and D. Also, A, B, C, D each has an equal resistance.

and for Part 2:

A and B turn off and C and D stay the same. The field still passes through C and D but not A and B.

Bulb B will not light up as the electric field around Bulbs A and B have been changed. Bulbs C and D still glow with the same brightness as potential difference across them is still the same.

Those who displayed aspects of previous models included:

Current is shared equally between all lights.

B remains the brightest bulb and C and D increase in brightness as there is more electric energy available.

In the above two sets of circuits, the resistors [R] are all equal in value. The light bulbs are all identical and the batteries are all identical.

For each set, use a number ranking (1,2,3...) to rank the bulbs from brightest (1) to least bright. If two or more bulbs have the *same* brightness, give them the *same* ranking number. Briefly explain your answer for Set 2.

Figure 4. Question 4: third trial. Series circuit. Adapted from Maloney (1986, p. 361)

In this circuit, all bulbs are identical.

a. For each bulb, use a number ranking (1,2,3...) to rank the bulbs from brightest (1) to least bright. If two or more bulbs have the *same* brightness, give them the *same* ranking number. Briefly explain your reasoning without using a formula.

b. What happens to the brightness of the other bulbs if Bulb A is removed from its socket? Explain, without using a formula.

Figure 5. Question 5: third trial. Series and parallel circuit. Adapted from McDermott and Shaffer (1992, p. 996)

Table 6. Question 5: post-test, third trial

	Correct ranking	Correct explanation	Partially correct explanation	Exhibiting aspects of Models 2 and 3
Group A	9	7	1	2
Group B	8	3	4	1

Once again, those reliant on a formula answered less well. Full results for Question 5 are given in Table 6. These results may be compared with the findings of McDermott and Shaffer (1992) who reported that amongst 500 university students tested on a comparable question, only around 15% successfully ranked the brightness of the bulbs. 'Whether the question is administered before or after instruction does not seem to affect the outcome' (p. 996).

From these responses, it seemed that those who had no previous experience were generally more ready to reason from a field perspective. Group B, however, who had a good command of formulae, tended to continue to try to reason from a current orientation and required much more explanation to resolve their difficulties.

Summary and Conclusions

The classes selected for these preliminary trials were not ideal. In the first trial, the Year 9 girls were constrained by the school's agenda for senior physics preparation and the students were a middle-achieving group without strong motivation to succeed in physics. The Year 11 class, on the other hand, while motivated to study physics and therefore already selective, was also a middle-achieving group. This class was very short of time to study the electrical unit and had to meet the requirements of an examination set by a teacher with a different approach to the subject. Both classes provided a testing environment in which to explore the feasibility of the field model.

The language used by the students and their improvement in post-test questions indicated encouraging outcomes. In the case of the students in the first trial, their ideas about potential difference were quite well developed after the teaching. The second group also adopted a voltage approach, despite their previous Year 9 experience with the electron flow model. The desired 'global' circuit view appeared to be attained by most of the two groups. While these results are based upon very limited evidence, they give some indication that the field model may assist the learning of simple circuitry in middle/high school.

In the third trial, Group A was directly comparable to the Year 11 students in the second trial. They had little previous experience and exhibited many traditional misconceptions about simple circuitry. The difference between them and Group B, who had a strong grounding in formulae, was marked; nevertheless, Group B had

difficulties when confronted with problems in which formulaic solutions were less simple. In summary, this class initially exhibited similar misconceptions in their reasoning to those in the previous two trials.

The following extract from an initially quite typical Group A student's examination paper illustrates the ability of the field model to explain the potential difference at various points in a circuit. While readily acknowledging that this explanation was an exceptional one, it nevertheless illustrates the possibility of sophisticated change. The explanation was constructed by the student from information delivered in the introductory lecture, not from formal notes, and represents his own synthesis of that information:

- (a) When the switch is closed, the magnitude of the potential difference across the battery is 1.5 V, across the resistor is 1.5 V, and across the switch is 0 V. Originally, there is an electric field across the battery and when the switch is closed, the electric field redistributes itself at the speed of light. Under the influence of the electric field, electrons start moving, and because the resistor and the battery are connected through wires, they almost have the same potential differences, so both the battery and the resistor have voltages of 1.5 V, but the switch becomes a wire, so basically there is a very small electric field across that, thus $V = 0$ for the switch.
- (b) When the switch is opened, the magnitude of the potential difference across the battery is 1.5 V, across the resistor is 0 V, and across the switch is 1.5 V. There is a gap in the circuit and electrons cannot get through the gap. But under the influence of the electric field, electrons will accumulate on one side and some of them will be drawn or repelled on the positive side. Eventually, they get a balanced amount of electrons and the voltage across the gap is the same as the battery, 1.5 V.

This is not the kind of language usually encountered in the electron flow model. It also constitutes a simple explanation. The field model clarifies many aspects that confuse students, such as parallel and series circuits, allowing them to explain what is happening rather than just accepting these complex phenomena. The model provides a seamless link from electrostatics to circuit theory. It explains why resistors get hot and why they transform energy. If high school students are introduced to the idea of a field in physics, then the language of fields may serve them well in gravitational, magnetic, and electrical theory. Suitable analogies appear to enhance this process.

The problem with universal adoption of the field model lies in its unfamiliarity. It is not within the 'comfort zone' of many teachers, nor, indeed, many conventional physicists for whom the electron flow model has proved comprehensible and satisfactory. The problems experienced by teachers will be described in a following paper—suffice it to say here that unless the advantages of the field model become more widely accepted and it is formally placed on the curriculum, it is unlikely to be adopted in our schools. It will require the development of new resource materials, including textbooks and practical exercises, and extensive professional development for teachers. If the model is to be adopted for high school students, it will therefore

be essential first to conduct more rigorous classroom trials with teachers who, like the three in this study, are willing to test new ideas.

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