COMPUTERS IN PHYSICS INSTRUCTION: STUDENTS' INTERACTIONS IN A CONSTRUCTIVIST MICROCOMPUTER-BASED LABORATORY

David William Alan Russell
DipT, BEd, GradDipEd(CompEd), MSc(ScEd)

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CERTIFICATE OF RECOMMENDATION

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ABSTRACT

This study aimed to increase understanding of students' interactions in a physics microcomputer-based laboratory (MBL) specifically designed to be consistent with a constructivist theory of learning. The study was motivated by a perceived need to understand better how the materials and strategies support or constrain students construction of understanding. The teacher-researcher conducted the study with two of his Year 11 physics classes, comprising 15 students studying thermal physics and 29 students studying kinematics. Dyads of students worked at tasks using a predict-observe-explain (POE) format as part of the normal class program. Data included video and audio recordings during four 70-minute sessions for each class, students' written notes, semi-structured student interviews, and the teacher's reflections on each session. The study describes the actors and network relationships during task activities. An analysis of students' discourse identified features common to both domains of physics, while the findings about student-display-teacher interactions are presented as a series of eight assertions. Finally, the researcher's interpretation of learning in an MBL leads to recommendations for teaching practice.

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PAPERS ARISING FROM THE RESEARCH

Russell, D., Lucas, K. B., & McRobbie, C. J. (1999, November). *Microcomputer based laboratory activities as catalysts for student construction of understanding in physics.* Paper presented at the annual conference of the Australian Association for Research in Education, Melbourne, Australia.

Russell, D., Lucas, K. B., & McRobbie, C. J. (2002, April). *Learning about kinematics in a microcomputer-based laboratory.* Paper accepted for presentation at the annual conference of the National Association for Research in Science Teaching, New Orleans, LA.

Russell, D., Lucas, K. B., & McRobbie, C. J. (2002, April). *Learning about thermal physics in a microcomputer-based laboratory.* Paper accepted for presentation at the annual conference of the American Educational Research Association, New Orleans, LA.

STATEMENT OF ORIGINAL AUTHORSHIP

The work contained in this thesis has not been previously submitted for a degree or diploma at any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

Signed:____

Date:____

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"In the multitude of counselors there is accomplishment" (Proverbs 15: 22). Nowhere is this more evident than in conducting research, and my counselors were the faculty members of the Centre for Mathematics and Science Education, Queensland University of Technology.

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND FOR THE RESEARCH

Computer technology is a protégé of physics. How appropriate it should be that physics instruction reaps the benefits flowing from its technological child. Of the many facets of computer technology, this study is concerned with the use of the computer as a classroom laboratory instrument, to translate experimental data into meaningful symbols. How these symbols catalyse student construction of understanding in physics is the essence of this research.

Since inexpensive Commodore and Sinclair personal computers appeared in schools twenty-five years ago the availability, affordability, applications and capabilities of computers have continued to expand exponentially. School science departments have witnessed a progression of diverse applications. Early initiatives were undertaken by a few technically minded teachers who used computers designed to store, manipulate and present data as basic displays of text. Simple word-processors enhanced teachers' clerical productions. In science laboratories computers were first used to make accurate time measurements, then record temperature and motion data. Now one generation later, science departments use computers for data spreadsheets, computer aided instruction, developing and evaluating models, multimedia, the Internet, electronic mail, interactive microworlds, experiment simulations and the microcomputer-based laboratory (MBL). The last of these is quintessentially physics technology applied to science instruction.

Laboratory activities are important to science teaching. "The laboratory sets science apart from most school subjects. It gives science teaching a special character, providing many teachers and their students liveliness and fun that are hard to obtain in other ways" (White, 1988, p. 186). In practice, laboratory work has often failed to live up to these ideals (Berry, Mulhall, Gunstone, & Loughran, 1999; Lazarowitz & Tamir, 1994; Tobin, 1990a). Negative aspects variously include repetitive and time-consuming data collection, a lack of satisfaction with measurements, and the time delay between conducting an experiment and processing the data (Lazarowitz & Tamir, 1994; MacKenzie, 1988).

School MBL technology provides powerful ways to resolve many of the difficulties and restraints relating to "ordinary" science laboratories. It has been claimed that the value of the MBL lies in the ease with which data can be collected and stored, the ability to access data over very long or very short time intervals, and the power to process and display data rapidly, thus providing more time for students to manipulate variables, test hypotheses, explore relationships, confront misconceptions, and develop skills of thinking (Kelly & Crawford, 1996; Lazarowitz & Tamir, 1994; Rogers, 1995; Thornton, 1987; Tinker, 1981). The possibilities are enhanced for reflection and discussion, for students to practise "science talk." All of these contribute to students having control over their learning and constructing their own meanings of science. A laboratory activity may be the highlight of a day at school ("Sir/Miss, are we doing an experiment today?").

The researcher has become aware of these changes in laboratory practice in the light of his experience with MBL methods over 24 years. He played a key role in introducing computers to his school laboratories 12 years ago, after extensive research into teachers' concerns with using this technology, and instituted an in-service program for the science staff. MBL methods are well established in the physics program of the school in which this study is based.

However, the reality is that relatively few science teachers have adopted MBL methods. The only Australian study documenting use of MBL methods that has been identified (Russell, 1991a) found that at that time only about 4% of science teachers in 44 Brisbane secondary schools had used computers in laboratories. Furthermore, using computers on one or a few occasions does not necessarily result in a teacher effectively incorporating computers into his/her normal teaching practice. For example, Clark and Jackson (1998) reported that time pressures and lack of computer training resulted in an enthusiastic teacher who collaborated with them in an MBL research study subsequently reverted to "his previous teaching philosophy and style" (p. 31). Other researchers (Roth, Woszczyna, & Smith, 1996) have found that disadvantages in terms of learning to manage the computer software outweigh the advantages.

Two reviews of the use of educational technology in science education (Berger, Lu, Belzer, & Voss, 1994; Linn, 1998) make little reference to MBL activities, concentrating more on interactive videodisk, telecommunication, and hypermedia applications. This is somewhat surprising because for many years persistent claims about the potential of computers in science education have been made (Bigum, 1998a; Nachmias & Linn, 1987; Thornton, 1987; Tinker, 1981; Weller, 1996) but the results of research into the effectiveness of computer based teaching strategies have been equivocal, especially in respect of science achievement (Berger et al., 1994; Dexter & Anderson, 1998; McRobbie & Thomas, 2000; Thornton & Sokoloff, 1990).

From the theoretical reference frame of constructivism (Appleton, 1997; Fensham, Gunstone, & White, 1994; Geelan, 1997), many of the positive research findings in support of MBL activities facilitating science learning can be interpreted in terms of the increased opportunities for student-student interactions and peer group discussions about familiar and discrepant events in relation to ready-to-hand data. However, there is convincing evidence that school science laboratory activities typically do not have this orientation (Nachmias & Linn, 1987; Tamir, 1991; Tobin, 1990a; Wilkinson & Ward, 1997; Woolnough, 1991).

It is possible that teachers' failure to utilise MBL activities more widely is a result of not recognising their capacity to transform the nature of laboratory activities to be more consistent with contemporary constructivist theories of learning. In recent years the need for researchers to study how students construct understanding of physical phenomena in MBLs has been recognised (Clark & Jackson, 1998; Nachmias & Linn, 1987). For example Driver, Asoko, Leach, Mortimer and Scott (1994, p. 11) argued "that the relationship between views of learning and pedagogy is problematic, and that no simple rules for pedagogical practice emerge from a constructivist view of learning." They concluded that one important role of the teacher was "to listen and diagnose the ways in which the instructional activities are being interpreted to inform further action" (p. 11). When the activities are microcomputer-based it is particularly difficult for the teacher to listen to students' conversations in order to diagnose how the computer mediated phenomena are being interpreted and then to respond appropriately. This hiatus provided the impetus for the research reported here, and also suggested the methodology adopted.

The present study is concerned with how students learn physics in an MBL specifically designed to be consistent with contemporary constructivist theories of learning, a "constructivist MBL" (cf. Roth's (1994, p. 1) similar description of a "constructivist high school physics laboratory").

The research is conducted in a naturalistic setting using video and audio recording strategies and contemporary approaches to analysing and interpreting data. The recommendation by Tobin (1990a) in his review of laboratory activities, as summarised by Lazarowitz and Tamir (1994), remains valid:

> Meaningful learning in the laboratory is possible. It is crucial that students reflect on their findings and consult a range of resources including other students, the teacher, books, and materials. Research is needed on how students engage, construct understandings, and negotiate meaning in cooperative groups and on how

> to guide teachers in establishing and maintaining environments conducive to learning. Teacher researchers are the logical inquirers in such studies. Collaboration among teachers and researchers is essential. (p. 95)

This advice is adopted by this teacher-researcher, as he incorporates the computer into collaborative laboratory activities, and investigates how students negotiate meanings in this context.

1.2 THE OBJECTIVES OF THE RESEARCH PROGRAM

This study seeks to document and interpret answers to the following questions. In an MBL specifically designed to be consistent with a constructivist theory of learning:

1. How do students learn physics?
2. How do the materials and teaching strategies support (or constrain) student understanding?

More specifically, pertaining to the first question:

3. What are the patterns of interaction between experimental phenomena, computer display, individual students, collaborative groups, and the teacher?
4. How are students' negotiations of new understandings mediated by the computer display?

The study has as outcomes:

1. The personal reflections of the teacher as researcher on his physics instruction.
2. A systematic documentation of ways by which students work effectively (or ineffectively).
3. Specific details of how the teacher acts to facilitate learning.
4. The development of appropriate pedagogical strategies incorporating MBL activities that will likely catalyse students' construction of understanding.

CHAPTER 2: LITERATURE REVIEW

This chapter begins by reviewing the early years of computer applications for physics instruction. It defines a microcomputer-based laboratory (MBL) and presents a general summary of the features and advantages of MBL techniques from the perspective of physics teachers. The chapter then reviews traditional quantitative research involving the use of computers in science laboratories, which emphasised comparison studies, graphing, and learning outcomes. Reviews of more recent studies evidence a change in methodology to qualitative studies of individual students and small groups in laboratories. Research into the roles of the computer monitor display in experiment simulations and hypermedia is examined briefly for its contribution to understanding student-monitor interactions. The fourth section of this chapter then examines two perspectives on how students construct their scientific views: as individual processes of conceptual change, and as collaborative social processes. Some difficulties in implementing a constructivist epistemology in science teaching are identified. A personal perspective on physics instruction is presented in the form of guidelines for establishing a constructivist MBL and the use of specialised student worksheets. The chapter concludes with a re-statement of the objectives of the present research.

The focus of the present study emerges from this review, which shows a knowledge gap in the ways students negotiate meaning and construct knowledge in the physics MBL.

2.1 COMPUTERS IN PHYSICS

Computers have been used in science education since the 1970s as a medium for computer aided instruction, spreadsheets, developing and evaluating models, multimedia, the Internet and electronic mail communications, interactive microworlds and experiment simulations. Microprocessors made their first appearance in school laboratories in the late 1970s as a tool to collect and display data. The now familiar acronym MBL was derived from materials developed at the Technical Education Research Centers (TERC, Cambridge, MA) around 1985. In his review of the impact of computer-based learning in science, Weller (1996) claimed "microcomputer-based laboratories (MBLs) hold out, perhaps, the most promising of all educational computing tools for providing the learner with opportunities to conduct science in both the context of discovery and the context of justification" (p. 472).

Notwithstanding the impressive potential that computer technology brings to the physics classroom and laboratory, many science teachers have remained conservative towards adopting MBL methods. Rogers and Wild (1994) noted that in the UK this was the situation through the early 1990s. In his 1993 review of the use of MBLs in the UK in the previous decade, Scaife (1993) stated that the inappropriate hardware and software available to teachers "had a negative effect on teacher morale and interest. It has taken schools several years to recover from this first experience of IT [Information Technology] in science laboratories" (p. 84).

In Australia, anecdotal evidence suggested that very few teachers had adopted MBL methods by the late 1980s. There were, or course, many reasons for this circumstance, and Russell (1991b) addressed some of these issues. These included science teachers' concerns with using technology and the lack of suitable software, hardware and computers for MBLs. However, the natural progression of technological development and teacher efficacy with computer resources has seen a change since that study. Indeed there is a current expectation by parents, principals and innovators that science teachers be proactive in utilising computer technology (Bigum, 1998a).

2.1.1 The microcomputer-based laboratory (MBL)

What constitutes an MBL? An MBL is a science laboratory which has, in addition to traditional resources, a number of computers with sensor interfaces that are used as laboratory instruments. In the broad sense of an MBL, the computers may be used to manipulate and present scientific data by means of their word-processing, statistical or spreadsheet functions. Additionally, they may display simulations of experiments that are otherwise difficult to conduct. Should the school be equipped with multimedia capable computers, students can experiment in a microworld – an all-engrossing interactive higher-level experiment simulation. Wiser and Kipman (1988) classified their interactive software simulations which differentiated heat and temperature as examples of MBLs. However, in the narrower but more accepted sense, as discussed from here on, an MBL uses computers to facilitate experiments. Sensor probes are attached to the computer for data collection during regular laboratory experiments. The computer does not replace experimental activities (as with a simulation). Rather, it becomes an instrument to complement experiments, though it would be correct to say that it modifies or extends the way in which many experiments are performed.

Apart from school and university teaching laboratories, professional scientists and commercial laboratories have long used MBL technology. In addition to pedagogical advantages, the MBL in school science departments provides students with authentic laboratory practices and preparation for possible employment in science or technology related fields. The evolution of interface technology and software from amateurish beginnings in the 1970s, to its present state of sophistication, will likely continue to the stage where the term MBL becomes redundant. Data logging, analysis and screen presentations of data may well become incorporated as de facto standard scientific apparatus.

School science department MBLs vary widely in the numbers and the types of computers they have available, which is determined in part by school funds and the available laboratory space. Many science departments make effective use of older computers discarded by other school departments. Virtually any working computer has a data recording speed quite adequate for the large majority of experiments. The advantage of later model computers lies almost solely in their enhanced screen display presentations.

Analog data are converted to digital data through one or more sensors linked to the computer through an interface. The interface may be attached inside or (more commonly) outside the computer. The sensors most frequently used in physics education measure movement, temperature, time intervals and light intensities. However, an extensive range of other sensors measures electrical values, pH, gas concentration, humidity, magnetic field intensity, and the list continues to grow annually.

Data are most usually presented graphically in real time, that is, without any apparent time delay between the student's performing the experiment and a graph being displayed on the monitor. Much less frequently, data are presented in statistical or tabular form. Software may allow the user to manipulate and analyse data further, and print hard copy.

2.1.2 Advantages of MBL methods

In their meta-analysis of research on using laboratory instruction in science, Lazarowitz and Tamir (1994) divided their review into three categories: (a) the United States and collaborators, (b) the United Kingdom and (c) Israel and Australia. Each of the first two categories drew mainly on research from their own countries of origin. Australian and Israeli research presented more internationally varied references. The paths of MBL use in the United States and the United Kingdom have also followed different trends in the development of hardware and software, pedagogical use and research methodology.

During the 1980s in the United Kingdom, hardware and software were developed by microelectronic engineers, and consequently their products proved unfriendly to students and teachers such that with few exceptions there was a general rejection of IT (Information Technology) (Rogers, 1987; Scaife, 1993). Nevertheless, and despite the lack of IT research studies in the UK at that time, proponents identified many apparent advantages in the field of datalogging, a term that closely identifies with MBL (Scaife, 1993).

In the United States a stronger general acceptance of MBL resulted from initiatives taken by a number of university science education centres (such as at the TERC) working in close conjunction with schools. Hence the major part of this review draws on published research from the United States.

It is helpful to synthesise the full range of advantages as identified subjectively by three authors from the UK and the US (Nachmias, 1989, cited in Lazarowitz & Tamir, 1994; Scaife, 1993; Thornton, 1987), and these are shown in Table 2.1.

Table 2.1

A Summary of Advantages Attributed to MBLs

Physical advantages conferred by the computer
Speed of data capture, size of memory storage
Processing and display of data with no time delay
Extreme times of data capture from microseconds to days
Large range of possible experiments, operating under extremes of environment
Data captured by multiple sensors simultaneously
Affective benefits to students
Hi-tech novelty, motivating
The ease of use reduces laboratory anxiety in less confident and underprepared students
Reduces wait time, and drudgery of collecting and processing data
Pedagogical gains
Students link graphic displays immediately to the experiment
Multiple representations of data, such as seeing a moving object and at the same time its displacement/velocity/acceleration graphs
Empowers students to investigate, repeat and control experiments, and focus on the meaning of the data
Peer learning is supported
Graphing skills and graph interpretation

Thornton (1987) argued that MBL tools may provide a direct experience with physical phenomena, and new ways to uncover the underlying principles of physics, in the light of the failure of traditional science instruction to alter student misconceptions and simplistic understandings.

Of the listing in Table 2.1, it is important to note that the physical benefits are unique to MBL technology as compared to other laboratory instruments. Of the perceived affective benefits and pedagogical gains, the only one linked by these authors to published research is the last one concerning graphs, and what has been studied in this area follows in the next section.

2.2 A REVIEW OF MBL RESEARCH

This section follows the approach by Lazarowitz and Tamir (1994) of reviewing research from the United States and from the United Kingdom separately, to reflect the different approaches in each country towards classroom implementation of MBLs and research methodologies. The reason for dividing the review into pre- and post-1990 is arbitrary, but to some degree it is evident that more of the research before 1990 was based on quantitative comparison studies, while the research post 1990 has progressively turned to qualitative methodologies. Particular attention is drawn to a number of interpretive studies using MBL methods that reveal students' behaviours and thinking during experiments. The present research will build on and extend the study by Kelly and Crawford (1996) which is reviewed as an exemplar.

2.2.1 Research in the US to 1990

During the 1980s many science teachers published journal articles that provided instructions for building simple interfaces. These teachers, out of enthusiasm for the new tool, related their personal classroom laboratory experiences. For example, it was found that the time saved in collecting data engendered greater student enthusiasm, laboratory work was more successful, and their students spent more time inferring, analysing and deducing (Jesberg & Dowden, 1986). Biology teachers related how they initiated MBL as a team effort and were so successful the methods spread to physics and chemistry departments (Westling & Bahe, 1986). Others (De Jong & Layman, 1984; Walton, 1985) both provided simple software directions to accompany their hardware diagrams. The many articles of this type provided literally scores of experiment descriptions for science students.

Accompanying these developments was an assumption that students must learn more and better by doing and seeing as they experimented. Much of the evidence was anecdotal and the teachers' claims seemed reasonable. Researchers in these early studies of MBL typically used observations and interviews, and quantified students' changes in understanding by statistically comparing pretest and posttest scores. Experiments most commonly involved motion and temperature sensors, due to their simplicity and easy application to familiar experimental problems. Tests and interviews were most frequently concerned with aspects of students' construction and understanding of graphs. Researchers drew on a large body of prior studies about the misconceptions and difficulties students have with motion, heat and temperature, and graph interpretation. A review of the articles published by researchers who pursued a continuing interest in MBL during this period follows.

2.2.1.1 Student learning with computer-presented graphs

The research by Mokros and Tinker (1987) was part of a five year program to develop curriculum materials for science education. In developing MBL materials the aspect of graphing was chosen due to its heavy emphasis in scientific practice, and the real-time evolution of screen graphs during the course of experiments. The researchers were aware that little was known about how graphing skills were learned and how graph production was related to graph interpretation. A preliminary study was conducted to find more about how children think about graphing. Interviews with seventh and eighth grade children revealed two major types of errors (Barclay, 1986). The first was that children confused the mental images of objects as they moved up and down, left and right, with the corresponding displacement-time and velocity-time graphs (graph as picture confusion). A second but less striking error was confusing information conveyed by the height of a graph with regions of maximum slope (slope/height confusion).

In a second preliminary study (Mokros & Tinker, 1987), sixth-grade children experimented with their body movements and a motion sensor. Students were asked to construct different types of graphs using their own body movements and the motion of a toy car, during which they were encouraged to make predictions. Over five days observers recorded their interactions, conversations and use of the equipment. They were then quizzed about their understanding of displacement and velocity graphs. Observations showed "many demonstrations of a solid understanding of distance and velocity graphs" (p. 374). Quiz scores indicated a very sound ability to interpret graphs of position and graphs showing positive and negative velocities. The main study was then designed to provide more evidence about the impact of MBL on graphing skills. Seven grade 7 and grade 8 classes worked for three months in an MBL using a variety of sensors. For example, during the heat and temperature unit children used pairs of sensors and heated water with immersion heaters. Multiple choice pretests and posttests were used to determine how their graphing skills developed over this time. The test items were in the form of written questions with and without diagrams, and students had to select an appropriate graph template. A "think-aloud interview" asked children to talk about generating hypotheses, observing, interpreting graphs and making conclusions. This was a quasi-experimental study with no control group. No information was provided about the comparability of the pretest and posttest instruments. Scores on 16 graphing items showed significant improvements ($p < .001$) between pretest and posttests in children's ability to interpret and use graphs. Children performed best when the rise and fall of the graph agreed with their mental pictures of something going up and down. Conversely, children scored lowest when the mental image was the inverse of the graph (such as picturing a ball rolling downhill, as against its velocity-time graph directed 'uphill').

Mokros and Tinker (1987) claimed that the two common graph errors identified in the first preliminary study "were not resistant to proper instruction" (p. 380) and they declined to label some common errors as misconceptions. Some caution is suggested in accepting the results due to possible maturation and instrumentation errors. Note should also be made that even after using MBL for three months, common graphing errors persisted for about one-third of the children in the study.

Discussing the results, the researchers described MBL as "a powerful vehicle" (p. 381) for teaching graphs for the following four possible reasons, which suggested future lines of research.

1. MBL uses multiple modalities. Children combine their kinesthetic senses by manipulating probes and equipment, with visual experiences by watching phenomena and graphic representations.

2. A real-time link is established between concrete experiences and their symbolic representations, which constitutes a bridging of concrete and formal operations.

3. Just as children learn grammar by reading and writing, Mokros and Tinker (1987) suggest that via the MBL they learn about graphing through the experience of gathering real data. They stated:

> Students bring a unique level of understanding of the data to the graph when the data comes from an experiment towards which students feel a sense of

ownership. Since MBL experiments *do not have graphing skill development as a primary goal* [italics added], students can use these graphs to understand phenomena. (pp. 381-382)

4. Lastly, students exchange the drudgery of graph production for repeated "what if" experiments. Indeed Mokros and Tinker argue that graph "penmanship" should be a minor exercise only after children understand the meaning and utility of graphs.

A study by Brasell (1987), described by Berger, Lu, Belzer and Voss (1994) as an "exemplary MBL study," addressed the following two questions: How will a single class lesson using a motion MBL with high school physics students affect their comprehension of distance and velocity graphs, compared with pencil-and-paper graph construction? What is the effect of real-time graphing as opposed to delayed graphing of data? Mokros and Tinker (1987) had suggested that the visual growth of the graph alongside the experiment facilitated a corresponding linking in memory. Brasell considered that children processed the events of graph-growth and experiment simultaneously and hence transferred information more easily as a unit into long-term memory. She surmised that the growth of the graph line drew children's attention to salient features of the graph.

These ideas were tested by comparing a real-time data display experiment with an identical experiment using delayed-time, to see which of the two would result in superior learning. A sonic rangefinder sensor was used to measure human movement in a line towards and away from the probe. The data were displayed as displacement-time or velocity-time graphs. The subjects were 75 physics students with prior instruction in kinematics. They were given time to familiarise themselves with the equipment and software. Worksheets were provided that included an activity to predict the graph due to a certain series of constant velocity movements, and an activity to reproduce a series of more complex movements. For the Standard-MBL group each 20-second graph activity was displayed in real time. For the Delayed-MBL group each point on the graph was displayed after the event, at a keystroke, point by point for 20 seconds. A third control group performed pencil-and-paper activities that mimicked the MBL groups. A fourth Test Only group completed pretests and posttests. Students were randomly assigned from each class into the four groups.

Different pretests and posttests were content-specific, requiring students to answer multiple-choice questions relating a verbal description of an event to its graphical representation. The posttest was in a different format to the pretest, which precluded direct comparisons of scores, but the pretest scores were used as a covariate. Analysis of covariance results indicated statistically significant positive effects with the Standard-MBL exercise on graphing achievement scores, as compared with the other treatments. Most of the improvement was on correctly graphing positive and negative directions of movement. However, all groups showed no evidence of improvement with the concept of graphing velocity. Students continued to select a sloping velocity-time graph to represent constant velocity. The Delayed-MBL group differed little from the pencil-and-paper control group in all aspects of the posttest. This study showed that real-time graphing of a motion experiment using a sonic rangefinder resulted in significantly better understanding of displacement-time graphs, though not with velocity-time graphs. Brasell (1987) conjectured that the delay in the monitor display inhibited students' graph skills because "it was long enough to have placed an additional information-processing demand on the students" (p. 393). Students had to recall their movement activity, then relate it to the graph. Brasell considered that the reasons for this were either lack of learners' motivation, limitations of their short-term memories, or non-awareness of the need to reflect on the completed activity. An important observation was that Delayed-MBL groups appeared to be "less actively engaged, less eager to experiment, and more concerned with procedural than conceptual issues . . . real-time graphing made the graphs appear more responsive, more manipulable, and more concrete" (p. 394).

There is, however, another aspect of the time delay that might have affected the outcome. Instead of taking a further 20 seconds to draw the delayed graph at the end of the experiment, the graph could have been displayed immediately the experiment concluded. Would this have maintained motivation? An artificially contrived delay might have introduced boredom and irritation factors, invalidating effects not common to both test groups.

The failure to detect significant improvement on velocity-time graph achievement may have derived from the single lesson exposure. Interviews also revealed that the students experienced procedural difficulties in performing the acceleration experiments, which resulted in less-than-ideal velocity-time graphs. In this study (Brasell, 1987) the participants were a select group of physics students (average age 17.7 years). Further studies with students of different academic levels and ages were indicated to better understand the effect of real-time as compared to delayed-time graphing on students' understanding.

No reports of a replication of this often-referenced study have been located in an extensive search of the literature. It is interesting to note that a 1987 study described as "exemplary" would not be so described if conducted ten years later. As will be seen later in the review, not only has the dominant research paradigm changed, but also a single lesson treatment would not be considered adequate. A differently designed study could provide a greatly enhanced understanding of the effect of real-time graphing on students' understanding.

Other studies have evaluated the use of probes and graphs associated with the temperature of water as it was heated and cooled (Nachmias & Linn, 1987). Four grade 8 classes of average ability participated in a one-semester study using MBL and four matched classes completed one semester using MBL with enhanced probes and instruction. The purpose of the study was to assess how students critically evaluated temperature-time graphs, the effect of extended MBL use on their critical evaluation skills, and the effect of enhanced instruction on these skills.

Results showed that children assessed the computer-generated graphs uncritically, much as they accepted without question textbook diagrams. Apparently the children assumed the graphs were reliable because they were computer-generated. Children had difficulty in diagnosing factors that made graphs look peculiar. After enhanced instruction the children were better able to identify irregularities and factors affecting graph scaling and shape. However, a rival hypothesis was that improvement was influenced by their using enhanced hardware and software, and not just the enhanced instruction. Children who tested ideas by changing variables came to revise their views.

In this study the aspects of graphs chosen for detailed attention were strongly influenced by difficulties encountered by the hardware and software developers of the era. These were the consequences that followed when: probe components were ill selected (not suited to the temperature range being measured); electrical connections malfunctioned; no algorithm was used to smooth digital data to an analog appearance; the software did not automatically scale temperature; and, the screen display showed a meaningless line when the graph over-ran the page boundary. None of these difficulties would confront students using hardware and software available in the late 1990s. This observation does not necessarily distract from the purpose of the study. However, what was tested for in graphing skills contrasted with the earlier study by Mokros and Tinker (1987), who chose to emphasise student understanding of the experiment at hand (as portrayed by graphs) rather than graphing errors deriving from software and hardware issues.

In summary, Nachmias and Linn (1987) identified fruitful directions of further research when they noted:

> These studies suggest the value of more detailed analysis of individual students as they perform laboratory experiments. Our interviews revealed glimpses of how students follow their ideas for awhile and then revise them, but these interviews do not provide enough information for us to accurately determine how individuals select the ideas they retain, or what conditions support conceptual change. (p. 504)

The data for this research report came from the CEG tests, and these gave no glimpse of the processes behind the change (and lack of change) in children's thinking, nor of the discourse between children as they worked in pairs at their computers.

During this same study Linn, Layman and Nachmias (1987) investigated MBL and graphing skills development from another perspective. The curriculum instruction for the heat and temperature experiments was designed around a "chain of cognitive accomplishments." These are links considered appropriate for learning about graphing. The four main links were: learning about basic graph features, familiarisation with a few simple graph templates (patterns or examples); applying templates to new problems, and solving graph problems in new domains. As one test of this curriculum approach, students were assessed as to how far along this hypothetical chain they were before and after the 18-week intervention. The multiple-choice test items included items for the steps (a) graph features, (b) temperature templates, and (c) the unfamiliar domain of motion templates. The students carried out 79 temperature and chemistry experiments that were graphed automatically.

The results showed that students made considerable progress in all three steps or links of the chain, as shown by improvements in raw score means. The improvement in student performance with motion templates was least marked, perhaps understandably, as the parallels between many aspects of motion and temperature graphs are extremely tenuous. The researchers concluded that MBL was effective for teaching graphing skills and subject matter templates. It appeared that students gained in their ability to interpret graphs, in context, and this is in agreement with the findings of Mokros and Tinker (1987). Students learned to assimilate mental pictures of graphs immediately associated with particular experiments. In particular, by displaying simultaneously two graphs, for example, the cooling curves of two unequal quantities of water, they gained a deeper understanding of experimental phenomena. The study did not shed light on "the mechanisms governing success of MBL," but the researchers suggested the computer display provided a "memory support" (Linn et al., 1987, p. 252) that facilitated learning.

To this point it is apparent that research into student learning with computer-presented graphs had sought to answer two questions: How effective are MBL methods at teaching graphing techniques, and how do MBL methods facilitate higher order skills of graph interpretation? Evidence was emerging that the strength of MBL was associated with graph interpretations. This led Rogers (1995) more recently to suggest that teachers "need to review the relative value they attach to different aspects of graphical technique" (p. 39), alluding to the slavery of attending to the technical details of graph plotting. Rather, he urged a shift "towards the development and use of interpreting skills to amplify the value of graphs as tools for scientific investigation" (p. 39).

2.2.1.2 The advantages of MBL: Seeking the source/s

In view of research that explored the benefits of MBL in the science laboratory, Stuessy and Rowland (1989) were interested in determining whether the advantages of MBL were embedded in its data logging capability, graphing capability, or both. Five treatments were designed around the study of heat of fusion and heat of vaporisation of pure water and saline water. The subjects were tenth grade high school biology students (n=75), the majority Hispanic. The students were randomly assigned into the five treatment groups. Group 1 used a laboratory thermometer, groups 2 and 3 used digital thermometers, and groups 4 and 5 used computer probes. Groups 1 and 2 hand-graphed results, group 3 entered data into the computer by hand to obtain graphs, group 4 viewed delayed-time computer generated graphs, and group 5 viewed real-time computer generated graphs.

Students' abilities to construct and interpret graphs were scored on pretests and posttests using a Graphing Skills Test (GST). The content test required students to describe in essay form what they observed in the laboratory. For the treatments, groups of two or three students were guided by written directions through a two-hour laboratory session. Means and standard deviations of gains on the GST, and of the Content Test were calculated for each group.

An analysis of variance of their scores on the Content Test data showed that the students who used a standard thermometer and hand graphed the results appeared to perform significantly better (p<.10) than all other groups. The significance is tenuous, considering the small size of each group (about fifteen students) and no evidence of the groups being comparable before their laboratory activities. However from this, Stuessy and Rowland concluded "that students learn more about latent heats when they are directly involved in data collection and data display" (p. 20). At this juncture it is important to differentiate between students' abilities to write about what they have observed, as opposed to what they have understood. The results of the content test as described tell little about students' higher order understandings of latent heat. Hence this conclusion is not supported by the data. For the same reasons the corollary to their conclusion, that "exposure to electronic equipment may negatively influence students' abilities to focus on the conceptual aspect of the laboratory" (p. 20), is also unsubstantiated.

An analysis of variance on the GST gain scores data showed that Group 5, which used real-time MBL graphing, appeared to score significantly higher ($p<.10$) than Groups 1 to 3, which used non-computer graph processing. Stuessy and Rowland concluded that MBL proved superior in enhancing the development of graphing abilities, a result claimed to be consistent with earlier findings (Linn et al., 1987; Mokros & Tinker, 1987). The GST was designed to test two different abilities, graph construction and graph interpretation. In this study no differentiation was made between graph construction and graph interpretation, only the latter being identified by Mokros and Tinker (1987) as being enhanced by MBL experiences.

Stuessy and Rowland tacitly recognised novelty as a threat to the internal validity of this comparison study, by suggesting that students be given ample prior time to familiarise themselves with new (electronic) equipment. It appears that unfamiliarity with the equipment was no hindrance to the graphing aspect of this study, yet the opposite was suggested for the content section of the study. This could indicate that whether a new medium has a positive or a negative effect on students depends on the task at hand and the learning outcomes being assessed. The degree of experience students have had in an MBL is an important variable that must be taken into account when designing research in this area.

Another study comparing MBL with conventional methods of laboratory graphing was that conducted by Adams and Shrum (1990). They investigated two different instructional effects on line-graphing skills and graph interpretation. The study was a four-hour intervention with 20 middle school biology students conducted in a clinical setting. The students were divided into high and low cognitive development groups as determined by their performance on a cognitive test (Group Assessment of Logical Thinking). Each half was then further divided by sex, and matched by scores on a multi-choice Test of Graphing in Science (TOGS). A single hour session of individual instruction introduced students to

MBL methods. Four hours of novel laboratory exercises were prepared for the study. Ten students completed their experiments using temperature probes and the graphing capabilities of the computers. Ten students collected data using thermometers, stopwatches, and pencil and paper. The laboratory worksheets focused on students' understandings of data and relationships on the graphs. The posttest instrument was an open-ended version of the TOGS that required them to construct and interpret line graphs.

Analyses of covariance procedures were used to analyse the data. The graph-construction part of the study was performed better by those students who practised conventional graphing exercises (effect size of – 1.01). Hence Adams and Shrum recommended that hand-graphing exercises should be maintained to teach graph construction. There was no statistically demonstrative difference in the graph interpretation ability of the MBL and conventional laboratory groups. In commenting on these results, Adams and Shrum claimed that students "had a 'mind's eye' picture of laboratory events not available to students conducting laboratory exercises in the conventional manner. They could realistically remember what the line on a graph did when they heated water." (pp. 783-784). The researchers presented no evidence to support this claim, which if true would have important implications for laboratory teaching methods.

The researchers reported a brief qualitative analysis of the MBL activities of students. Observations of students' actions and interviews about their experiences were recorded. No information was provided as to whether students worked individually or as groups. An analysis of the data revealed that during the early stages students carefully watched the computer graphs develop, and by the second hour their gazes tended less to the computer display and more towards experimental phenomena, laboratory notes and other tasks. "The students' attitude towards the computer seemed to be that it was now a tool . . . to perform tasks for them" (p. 785). This raises a number of important questions and possibilities for future study. Based on the researchers' claim that the experiment and display left students with a "mind's eye" impression of events, then the computer would have played a more powerful role than that of a mere tool. What was the role of the display in mediating their learning? What were the thought processes of students during the experiments? It appears that the five students in each of two groups watched "a computer," and if so any conversation would have been important to record and analyse. This calls for an interpretive study using discourse analysis methodology, and current practices would situate the laboratory activities conducted within a constructivist framework.

A study by Beichner (1990) was founded on the base provided by earlier research which claimed that simultaneity of graph construction with an experimental event aided understanding and long-term memory (Brasell, 1987; Mokros & Tinker, 1987; Thornton, 1987). Beichner sought to isolate the aspect of MBL real-time graphing that accounted for better student achievement. He postulated that if contiguous perception of the movement of an object and the growth of a motion-time graph was the key, then an action video could be exchanged for students actually moving an object to achieve the same result. Should this prove to be true, Beichner considered other possibilities for using videos in place of MBL experiments. Distance learning in non-laboratory surroundings would be able to substitute videos for actual experiments. Computer disks with video scenes of moving objects might replace MBL methods. The study sought to answer the question: Would a motion video/computer display combination prove more effective than traditional pencil-and-paper techniques in teaching students motion graph interpretation skills?

The video presentation showed a ball traverse the screen at the same time as the computer generated displacement or velocity graphs. Replay, pausing, and analyses of slopes and areas under graph curves were controlled by students. The traditional group used as data sources stroboscopic photographs of a ball thrown in an arc, from which they drew their own graphs. All high school and college students (n=237) completed the same worksheets, which tested their interpretations of motion events. Students who viewed a video animation of motion did not learn significantly more than students who processed the stroboscopic photographs and drew their own graphs. Nor did students who witnessed a real motion event perform significantly better than those who did not view a ball thrown. The only hypothesis that was supported was that students, regardless of type of treatment, learned overall.

Beichner (1990) offered two reasons for the value of MBL methods. The first was associated with the opportunities they gave students to control the motion event and see immediate feedback. The second was the linking of visual and kinesthetic feedback. These are speculations, and both apply to using a sonic ranger motion sensor that is activated by students walking back and forth. Beichner suggested a range of comparison studies to tease out the aspects of MBL motion experiments that promote learning. Considering the range of variables (amount of student control over experiment, generic type of motion sensor, types of experiment performed and so forth), this could entail an enormous amount of research, particularly if longer-term interventions are used. Then, as Beichner pointed out, not all MBL experiments involve such a strong kinesthetic sense, as is the case when using body movement with a sonic sensor. Studies of the types by Beichner (1990) and Brasell (1987) could well be extended to temperature and light sensors, which do not involve students' physical movements.

Beichner (1990) suggested that the quality and design of screen presentation might be important: Would the display of more than one graph, or overlaying graphs, allow for easier comparisons, or result in distraction and confuse understanding? Would students react differently to higher quality animations and more aesthetically pleasing screen presentations? Reiber et al. (1996) noted that constructing an effective interface for simulation displays was a formidable task. Software authors are faced with a vast range of options in designing the visual interface – the balance between presenting data as text or graphics, the degree of guidance offered the user, and the skill level required to navigate through screen selections. Drawing from a different context, Irvins (as cited in Taylor, 1987), a former Curator of Prints at the Metropolitan Museum of Art in New York City, stated: "In a way . . . the accepted report of an event [in his case prints] is of greater importance than the event, for what we think about and act upon is the symbolic report and not the concrete event itself" (p. 210). Taylor claimed the computer graphic display might also be taken as "the symbolic report" of an event in physics, which is acted on and hence becomes more real than the physical experiment. Though many of the above observations concerned simulation displays, they are equally applicable to MBL screen displays and will be considered later in more detail.

Beichner noted that computer-using students completed their worksheets in a much shorter time than pencil-and-paper groups. The time saved is not of course measured by traditional pretest-posttest analyses. No report was made of what these students did in the saved time. Though this study failed to show the video/computer group delivered more effective learning, it may have delivered more efficient learning, defined by Berger et al. (1994) as "more learning in the same amount of time or the same learning in less time" (p. 466).

2.2.1.3 The development of an MBL curriculum

By the latter half of the 1980s a number of centres of mathematics and science education in the United States had trialled and refined secondary and tertiary MBL physics laboratory curricula. The report by Thornton and Sokoloff (1990) described part of one such curriculum, the motion studies section of the "Tools for Scientific Thinking" project.

> A visit to an MBL laboratory illustrates the contrast with a traditional class. Students are actively involved in their learning. They are sketching predictions and

> discussing them in groups of two or three. They are appealing to features of the graphs they have just plotted to argue their points of view with their peers . . . there is a level of student involvement, success, and understanding that is rare in a physics laboratory . . . the tools, the curriculum, and the social and physical setting – are primarily responsible for the learning gains. (pp. 862, 866)

The rationale for this MBL curriculum was based on the current mature state of hardware and software development, and the capacity of MBL methods to deliver to students those experiences identified by educational researchers as being essential to development of particular physical concepts. The laboratory activities as described exemplified a number of features that contrasted with practices of five to ten years earlier, these being: (a) Experiments were directed at student involvement and understanding rather than development of laboratory techniques; (b) the available hardware and software were apparently fault-free so that experiments no longer required students to identify graph errors originating from poor hardware or software; (c) instead of graph plotting, scaling and fault detection exercises, students gave their attention to screen patterns and what these said about the motion of objects; and (d) investigation, prediction, explanation and varied repetition generated enthusiasm. Extensive pretests and posttests of physics students provided "strong evidence for significantly improved learning and retention by students who used the MBL materials, compared to those taught in lecture" (Thornton & Sokoloff, 1990, p. 862).

2.2.1.4 A summary of US research to 1990

MBL research in the US to 1990 focused almost solely on MBL effects on students' graphing skills. All of the studies used quantitative methods based on the analysis of pretest and posttest data, and one half of the studies were brief one to four lesson interventions. Less than one half of the studies analysed observation and interview data, and in these cases analysis played a minor role in the research. In each study clear written directions were provided, and students recorded results in various forms. No study compared individual with group learning activities, or made a detailed analysis of individual students as they performed laboratory experiments. The findings established that MBL methods saved students' time in the laboratory, and were effective in teaching graph interpretation and overcoming some displacement graph misconceptions. The real-time graph aspect identified by Brasell (1987) with persuasive support from other studies (Adams & Shrum, 1990; Stuessy & Rowland, 1989) attracted most attention from researchers in this field.

2.2.2 Information Technology (IT) in the UK

Information Technology (IT) in UK schools is a broad term that includes MBL as a sub-set. Many of the journal reports on IT describe how to interface and conduct particular experiments (Larminie, 1980; Needham, 1986; Williams & Cluskey, 1989; Winn, 1990). Comparatively few articles discuss research into the value of IT to science instruction. This is probably due to the slower uptake of MBL and a different approach to research in the UK as compared to the US.

In one study (Solomon et al., 1991) a group of teachers rejected the traditional research genres of the types described in the previous section, in favour of an empirical approach determined by their classroom knowledge, strategies and agenda, by which they could explore the learning produced. Teachers provided their classes with a motion sensor for a single lesson, and observed how pupils used it and the software. The students in two advanced-level physics classes were delighted with the superiority of the sensor over ticker-timers, and executed a creative variety of exploratory motion experiments. Three year nine and ten classes used the sensor in unstructured settings. In one class pupils were invited to "come out front and have a go." Understandably many were shy and hesitant. In the second class, groups of three matched their body movements to preset displacement-time graphs on the screen, then became bored. In the third class the teacher used the motion sensor in place of a ticker-timer and conducted a demonstration lesson asking pupils to predict graph shapes. The year seven pupils had no prior knowledge of motion theory. Working in small groups, they thoroughly enjoyed the fun of the "brilliant game" and joined in with lots of talk. Beyond these observations, there was no measure of what learning took place. To quantify some outcomes, two teachers carried out studies with a Year 7 class. For twenty minutes the class mimicked nine pre-set graphs using one motion sensor, and five days later the children were tested for memory of the interaction and extension to new applications. On both grounds the teachers judged the results as disappointing, based on a mean correct score of 21% for the five questions. A term later the same pupils repeated the activities and completed worksheets. After five days they completed the same test as earlier and the mean correct score on the same five questions was 45%. This result does not of course take into account the experiences the children had in the intervening period. The second teacher divided a class into matched groups (based on Scholastic Aptitude Test scores), and one group used the worksheets. The worksheet group mean score was 65% as compared with the non-worksheet mean score of 42%. The experimental designs were rudimentary; nevertheless they suggested that more durable learning took place when a worksheet was used. The authors concluded that doing was not enough, and some formal written expression was needed for memory to work effectively. Data gathered during one lesson using a single sensor in a novel situation was unlikely to provide helpful directions for MBL and physics education, particularly so when the pupils' experiences were unstructured.

Laboratory observations by the researchers and teachers in the two studies just reviewed were similar to many of those made by their US counterparts (for example, Beichner, 1990; Nachmias & Linn, 1987; Stuessy & Rowland, 1989). It was found that pupils required (a) time to learn IT methods, (b) worksheets that guided and prompted inquiry, (c) skilful questions posed by teachers, and (d) more exposure to IT to benefit from the results. The benefits to pupils were that they (a) spent more time discussing results, (b) improved their interpretation of graphs, (c) increased science talk since results were immediate, and (d) the quality of data guaranteed a successful lab.

These two reports are illustrative of the approach to MBL research in the UK. Research seemed to rely very much on the teacher-researcher's professional judgment concerning learning outcomes. The significance of this is that, for the present study, the professional judgment of observations by the teacher-researcher is worth reporting.

2.2.3 Research in the US after 1990

In the 1990s, studies continued to evaluate various MBL instructional delivery techniques and comparisons. For example, Roth, Woszczyna and Smith (1996) unfavourably contrasted the confined space for student conversation around a computer with that around a large concept map. Redish, Saul and Steinberg (1997) used pretest/posttest measures to compare engineering students' understanding of concepts in mechanics while using MBL equipment and traditional presentations. However, of comparison studies (that is of one delivery medium or technique versus another) Berger et al. (1994) said:

> [These] do not necessarily provide a link to or understanding of what is going on while students are learning using instructional technology. Even the best pre-post randomised designs cannot answer such questions. By accompanying a detailed analysis of students' interactions with the computer . . . a start to analyse student learning during the experience with technology can be inferred. (p. 476)

Weller (1996) also warned that comparison studies were "vulnerable to . . . the possible uncontrolled effects of instructional method and novelty" (p. 462).

The review by Berger et al. (1994) identified "a shift toward new uses of instructional technology. They include studies where comparison studies are not appropriate because there are often no analogs for instruction outside the use of technology" (p. 466). Research in the 1990s has come to be more directed towards non-comparison research on MBLs using qualitative methodologies. Specifically, snapshot monitoring of students at specific points in time, whether by test or interview, has been supplemented or replaced by a continuous recording of the process by which students alter their conceptions through time (Weller, 1995).

Although Nakhleh and Krajcik (1994) studied the contribution of MBL methods in a chemistry context, the information conveyed by the screen display differed in no way to that of many physics experiments. Their study was noteworthy for two reasons: firstly, because it sought to establish that MBL technology conveyed a "higher level of information" than other laboratory instruments, and secondly its method of data gathering differed from that of former studies. Fifteen middle-achieving Year 11 chemistry students were divided into three groups and performed a series of titration experiments individually. When used to measure acidity concentrations in a titration experiment, the monitor displayed the current pH value and a real-time graph of pH versus the volume of base formed as the titration progressed. The slope of the graph gave the volume rate of change of pH. The first group used the MBL pH sensor. The second group used a pH meter with analog scale and the students were able to watch the needle move during the titration. The third group of students used chemical indicators and observed colour changes. It was theorised that the three measurement procedures used by the three groups offered students "levels of information" in decreasing order. The purpose of the study was to investigate how the different levels of information as presented by three different media affected students' understanding of neutralisation concepts.

An initial semi-structured interview probed each student's understanding of acid-base chemistry. The students then performed three titrations individually, and were interviewed again following a similar format to the initial interview. The researchers constructed concept maps based on the interviews, to represent each student's understanding of the chemistry involved. The initial and final concept maps were scored to quantify individual and average gains across the three technologies used. An analysis of these scores showed the technologies provided different levels of information about acid-base chemistry. The researchers suggested that the MBL display left the most enduring visual image for students to analyse, and the pH meter only a transient image. They suggested that the MBL students were more actively involved during the tasks, and that they generated more concepts and propositions, some appropriate and some inappropriate.

The researchers concluded that laboratory tasks required support by teacher-mediated instruction during experiments, pre-laboratory and post-laboratory discussions to counteract the formation of inappropriate concepts. They also surmised that the computer display maintained a temporal record of events, which allowed students more time to reflect and predict. “It may also be that the visual image of the graph screen is sufficiently vivid to be retained as a strong and easily retrievable memory” (p. 1095). Three directions for research were identified. The first related to effective methods of using MBLs in teaching. The second related to the features of MBL that appeared to enhance learning, particularly the screen display. The third was the need to understand students’ thoughts during laboratory activity. Each of these recommendations is central to the methods and aims of the present research. An analysis of student think-aloud protocols indicated that the MBL students engaged in more meaningful speculations and predictions. The researchers proposed that the MBL students’ short-term memories were freed to reflect on their activities; also, that the monitor display was sufficiently vivid to be retained as a strong and easily retrievable memory.

Another report on the same study (Nakhleh & Krajcik, 1993) analysed structured observations gathered by video and audio recordings of students’ think aloud commentary. The videotaped records captured the correspondence between students’ actions and their commentary on their thinking as they performed activities individually. The tapes were transcribed and coded by the categories. These were procedural statements, analytical statements, emotional statements, adequate understanding and inadequate understanding. These data were consistent with the conclusions taken from interview data in their later report (Nakhleh & Krajcik, 1994), namely that the computer seemed to function as an auxiliary memory to which the students could refer at any time. By contrast, the pH meter group could not do this. Consequently, the MBL group could focus their thoughts on what was happening (as in the continuous tense for progressive action) as opposed to action completed in the past.

The videotape and audiotape methods of Nakhleh and Krajcik (1993) were used also by Settlage (1995) during an eight-week unit of third year pupils’ study of the behaviour of light. The children viewed screen displays of both bar graphs and what was for them a new experience with line graphs. It appeared that the children learned about line graphs inductively, without prior instruction on point plotting. Secondly, the children developed their science talk, a “graphical literacy” in this case, as they worked cooperatively. Thirdly, MBL provided a tool for investigations, promoting deeper understanding in this instance into the behaviour of light, and contributed to increased scientific inquiry.

Roth et al. (1996) shifted attention from studying the cognitive achievements of students interacting with computers to investigate the roles of the computer in contributing to group interactions and learning in a physics course. While the students in their study used a sophisticated experiment simulation, an interactive microworld, some aspects of their study are relevant to MBL applications. The commonality is that both carry messages via the screen display and facilitate science talk and group interactions. The subjects of the study were 46 Year 11 introductory physics students. Students were videotaped during three one-hour sessions and their talk and gestures were analysed to provide some indication of their knowing and learning processes. The researchers found that the dynamic microworld environment facilitated group discussion, and allowed students to bring together phenomenal and conceptual domains (pictures of moving objects and the physicist’s symbolic vector drawings). The researchers suggested (indirectly) that MBL might have the capacity to present the phenomenal rather better than a simulation, the real events of actual experiments in place of computer-generated diagrams. They also found the proximity and endurance of screen representations maintained conversational cohesion such that students were rarely off-task.

The computer, however, hindered student interactions for two reasons. Firstly, students received too brief an introduction to the software, which proved to be rather complex. Advanced simulation software contains within it inherent difficulties, both of nested levels of navigation, large numbers of keystrokes that take time to learn, and screen messages that can be ambiguous. These types of difficulties will likely be exacerbated with time as microworld programs permit users to explore even more complex interrelationships. On the other hand, MBL software requires fewer familiarisation skills and has a much lower level of complexity, in that its prime function is simply to present graphs. For example, the study by Settlage (1995) with a third year class evidenced the speed with which children learned how to use the equipment, and this can be taken as typical of MBL. Nevertheless prior experience in an MBL is important to obviate novelty effects when planning research with students.

The second constraint identified by Roth et al. (1996) is legitimate when applied to MBL, and that is the matter of crowding more than two students around a computer. In their study the necessity of crowding three to five students affected group interaction and conversation. Those students further from the screen were excluded from collaboration. The reason for crowding was evidently one of logistics, related to the availability of MBL equipment. Should the class being studied have had sufficient equipment to allow two students per computer then without doubt this difficulty would hardly have arisen. The reviewer has sighted no reports of studies exploring optimal numbers for collaborative group working in an MBL.

A one year case study by Clark and Jackson (1998) investigated the impact of technology in Year 9 physics classes to determine any effects on student motivation and concurrent cognitive changes. Sources of the data included observations, interviews, group focus discussions and video recordings of laboratory activities. The study found that their students showed positive motivational gains when using MBL methods, after they had gained sufficient experience using the equipment. When the technology gave clear results, such as a temperature-time graph of the phase change of melting ice, students expressed confidence in the accuracy of computer measurements (which contrasted with traditional methods of measuring). This confidence contributed more to their changing alternative conceptions than did classroom lesson dialogue, according to the students' own expressions. They attached considerable importance to the real-time nature of data presentation. Further, students "simply enjoyed working with the computers" (p. 14). The authors reported this affective response actually increased throughout the year.

It is notable that these students used temperature and motion probes, both of which assisted understanding, yet only the latter involved the kinesthetic sense of body movement. Beichner (1990) had suggested "kinesthetic feedback could be the most important component of the MBL learning experience" (p. 803). Whether full body movements in front of a sonic ranger contribute more than all the other physical manipulations that are a part of experimenting remains a moot point.

Clark and Jackson (1998) identified a number of adverse aspects proceeding from the technology. As with some earlier studies it was found that experiments that were too unstructured left students puzzled. To achieve maximum effect, instructions for use of the equipment and procedures for the experiments at hand needed to be such as to reduce the cognitive demands on students. Though the software used in their study was "user friendly for an experienced scientist, it was not at all intuitive for the teacher or the students" (p. 15). Student frustration arose from occasional erroneous results caused in the most part by cross-interference of sonic data from different student work stations and, from the viewpoint of a software programmer, the lack of error-trapping routines in the software (see also MacIsaac

& Hämäläinen, 2002). Teacher frustration due to a lack of confidence in and with hardware and software, though not called such explicitly in this study, again presents itself as a serious detractor from teacher uptake of MBL (Russell, 1991a).

Clark and Jackson (1998) concluded that a better understanding was needed of how students make connections between MBL activities and experimental phenomena, so as to better inform teachers committed to a constructivist approach to science instruction.

2.2.3.1 A summary of MBL research after 1990

An outline of the findings of each of the MBL studies reviewed thus far appears in Appendix 1. A number of common threads can be discerned from this research, and a general consensus as to the positive contribution of MBL methods would be as follows:

- MBLs enhance skills of graph interpretation, but mastering the skills of drawing graphs is better learned using pencil and paper;
- MBL methods save students time, allowing them more opportunities to discuss and investigate phenomena;
- MBLs motivate students, giving a feeling of having more control over their experiments, and greater confidence in the accuracy of results;
- the display acts as an auxiliary memory, lightening the cognitive load on students; and
- the real-time graphing capabilities play an important role for improving cognition and motivation.

A number of lessons can be learned by teachers using MBL technology.

- Students need time to become acquainted with hardware and software for laboratory activities to be enhanced.
- Students benefit more if they have introductory instruction in theory prior to laboratory activities, and require clear instructions in the form of worksheets, so as to avoid frustration at completing their tasks.
- The teacher needs to mediate when necessary to provide a measure of direction and correction of false conclusions. The effectiveness of MBL instruction seems to depend on the teacher's use and knowledge of the technique (Krajcik & Layman, 1989) and the instructional sequence surrounding laboratory activities (Krajcik, 1991).
- Student groups are best kept to fewer than four students to each computer.

In her projections for future directions of MBL research, Nakhleh (1994) identified a need for naturalistic studies in the real-world environment of the classroom laboratory. Many of the studies to date had focused on narrow achievements using multiple choice tests, were clinical settings with students and teachers having no prior instruction, using only one probe, and concentrating on how well students could draw and/or interpret graphs. She held that research was needed to focus on how students construct knowledge using MBL, how MBL affects students' perceptions and interpretations of physical phenomena, and how students make connections between graphs and the physical phenomena the graphs represent.

2.2.4 Interpretive studies of MBL

Seeking to understand how science students learn and how they construct knowledge while using computers has led researchers to use a range of strategies drawn from the social sciences. One productive approach is known as "protocol analysis, where the pronouncements and actions of subjects are carefully scrutinised for moment-by-moment flow of problem solving activity, or in order to discover and verify the use of particular knowledge schemata" (diSessa, 1987, p. 346). Here diSessa posits that qualitative knowledge is a prior requisite for any quantitative understanding. The latter constitutes the tangible results of a special treatment or technology, measurable to a certain probability level, but empirical knowledge does not reveal the processes of building mental constructs and how collaborative groups negotiate meaning. Nachmias and Linn (1987) examined how students evaluated temperature graphs in an MBL using traditional assessment items. However, interviews of a small number of students revealed information about their complex understanding of the physics of heat and temperature and graphic displays. They concluded, "these studies suggest the value of a more detailed analysis of individual students as they perform laboratory experiments" (p. 504).

Four of the research studies reviewed above (Clark & Jackson, 1998; Nakhleh & Krajcik, 1993; Roth et al., 1996; Settlage, 1995) used videotape technology to record and analyse students' discourse and behaviours in an MBL environment. In one of the earliest science laboratory applications of videotapes and audiotapes, Nakleh and Krajcik (1991) investigated how well students' verbal commentaries agreed with their actual behaviours while using MBL. They also gained some insight as to the different types of thoughts that were associated with short-term memory. Roth et al. (1996) noted that prior studies on computers in science education had focused on the comparison of student outcomes and the skills students showed after computer instruction. Their use of videotapes provided them with a means to increase understanding of the roles of the computer in small group activities.

Qualitative methodologies are being increasingly utilised to this end. Berger et al. (1994) videotaped students in MBLs to increase their understanding of what was going on during instruction and how students built and linked concepts. Weller (1996) recommended using such technologies to

> examine many variables over a long term, gleaning a rich harvest of data . . . (to) yield more informative information. The future may bring much more use of qualitative methodology to inform studies of the highly complex computer-based science learning experience. (p. 481)

Speech analysis techniques have also been used to examine patterns of student interactions as they solved simulation problems in an astronomy laboratory (McLellan, 1994). Videotapes of 19 student pairs were coded and analysed by a computer system PLEXYN for frequency of selected actions. These included 23 subcategories of verbal communication, locomotion, gestures and focus of attention. In addition, subject-object interactions were coded. Subjects included humans; objects included keyboard, joystick, screen, worksheet, pen and wall chart. In all but two of the 19 pairs, one partner dominated control of the keyboard or joystick. A further analysis compared the high and low controllers as regards their interactions with partner and screen. Students in control of the keyboard gave more answers and explanations. Explanations outnumbered brief answers by 3.5 to 1, although the quality of questions and answers was not determined. The students classified as low computer controllers showed the highest incidence of asking for assistance. Some students showed a high degree of interaction with other screens, primarily to offer assistance, and occasionally to verify something. Help was more often sought from a partner than from the teacher, though this reflected closely the ratio of student pairs to teacher. The study confirmed the value of students working with partners at a computer, and illustrates an application of statistical analysis of social interaction in a computer laboratory. McLellan recommended designing interaction into worksheet requirements and activities that more equitably shared involvement.

2.2.4.1 An exemplary study

The study by Kelly and Crawford (1996) well illustrates the use of video and audio technology, by which students' discourse was recorded and analysed systematically during a course of physics instruction in an MBL. The researchers began with the proposition that students are acculturated into the scientific community through sharing in science discourse – identifying problems, deciding on solutions – during which they develop shared scientific constructs and a perspective on the nature of scientific inquiry. Their ideas were formed in the context of group laboratory activities. Kelly and Crawford (1996) selected an MBL setting for two reasons: It allowed students more time for cycles of data gathering and associated reflective discourse, and the screen of the computer displayed symbols which required student interpretation. "Students need to talk curves and squiggles into concepts and ideas" (p. 696). An advanced physics class used the MBL to study oscillatory motion and the associated motion graphs. The students were given time initially to gain familiarity with the interface and motion detectors. For the formal study they experimented with masses oscillating on springs, and were required to analyse displacement, velocity and acceleration graphs. Four laboratory groups of three to four students each were captured on videotape as they worked in front of the computer monitors, during a total of four lessons.

Patterns of interaction within small groups were studied by analysing transcripts of dialogue taken from the videotapes and audiotapes. Non-verbal clues to students' actions and displays on the computer monitor were added as annotations to the transcripts. The analysis used multiple levels of interpretation that included message units, action units, interaction units and sequence units in order to understand the use of language in classrooms. Their study made apparent students' conceptions in science, understanding of the tasks, and negotiation of their roles.

Further analysis also revealed interesting patterns of interaction between the students and the monitor display. The computer representations entered students' conversation via two pathways. By the first pathway, the computer displayed data graphically and acted as a (silent) member of the group. The screen display (a) helped students in various ways to support their arguments, (b) helped students construct meaning of various concepts, (c) exhibited data, (d) elicited student responses, and (e) presented students with unexpected results. Via the second pathway students acknowledged the computer presentation, responding in a number of ways. These were: (a) using the display to support a claim about the experiment, (b) making a prediction, (c) demonstrating by reference to a feature of the graph, (d) clarifying ideas by appeal to the graph, (e) reading data, (f) responding directly to the computer, and (g) acknowledging anomalies in their own concepts or expectations due to the evidence of the computer display. Individuals and groups varied in the extent and manner by which they referred to the computer.

This analysis examined the interchange between students and the display and the inter-dependence of each in a techno-social group. The computer held the special position of being the unquestioned authority. The students ultimately had to resolve their own understandings and conclusions. Kelly and Crawford (1996) did not report an analysis of inter-group discourse or teacher-student interaction. The methodology did not concern itself with the differential between a pretest and a posttest, but rather with the processes of incremental changes in students' understanding. The procedures used suggest that theirs was a fruitful approach towards understanding the roles of the computer in group experiments than customary quantitative methods.

This study by Kelly and Crawford (1996) provides a model for the present research as regards its theoretical foundation, and research methodology. The present research will extend the data analysis to report on intra-group and teacher-student discourse, conducted by the teacher-researcher over a longer period of time and across two areas of physics.

2.3 THE ROLES OF THE COMPUTER DISPLAY

As the role of the screen display in mediating learning is central to this study, a brief review now follows of four studies that examined student-display interactions in contexts similar to MBL. These studies contribute to the methodological approach to discourse analysis in the present research. Some recent theoretical perspectives on the role of the display are also presented. They are the display as a legitimate group member based on actor-network theory, and the unique aspects of the display as a learning medium.

2.3.1 Student interactions with simulations and multimedia

Simulations are computer programs that allow users to manipulate variables in a representation of a physical world or a theoretical system. The point of commonality with MBLs is that both convey information by a screen display with its symbols and graphs. If the MBL setting can be seen as a set of interactions between two students, a monitor and an experimental apparatus, then the simulation exchanges the keyboard for the experimental apparatus. The exchange is very significant: Compared to a keyboard, science equipment may well be bulky, more interesting visually and tactually, and be more closely attuned to real-world experiences or applications. Nevertheless, studies of user-interactions with simulation displays are pertinent to the present discussion, for what can be learned from both the methodologies used and specific findings.

Roberts, Blakeslee, Barowy, Grosslight and Theberge (1994) studied the dynamics of mental-model development as middle school students used simulations to learn science based on wave motion and population growth explorations. During a series of simulation lessons, a teacher/researcher used an intervention approach and conversed with groups of two to four students, eliciting their reasoning and posing problems while they worked. The videotape analysis suggested that students progressed through three stages as they gained familiarity with the simulation packages. They were: (a) unstructured software exploring to understand how changing the keyboard variables affected the graphic output, (b) comparing new with prior results and creating analogies, and (c) using the simulation model to test ideas and to hypothesise. The research questions addressed in this study did not extend to the nature of the interactions of students with the simulation displays, which may well be (as the research team noted) better understood by looking at the videotapes from another perspective. Such an analysis would be limited as the intervention approach restrained natural classroom student-student-computer interactions.

More pertinent to meanings attributed to the monitor in science simulations was the use by Horwitz, Taylor and Hickman (1994) of simulation software. Two classes of high school physics students experimented with a simulation of objects moving at relativistic velocities in different reference frames. Classes followed this format: The teacher presented a problem or paradox; the students working in groups of two or three devised a thought experiment; each group ran the experiment as a simulation; and finally each group reported its findings. Post-experiment interviews and a test to evaluate students' understanding of relativity were conducted.

> When we asked students what taught them the most, they replied the process of writing their report, which took place without benefit of the RelLab display. This reminded us of an observation made during earlier class discussions of paradoxes: *students seemed able to play out scenarios in their heads, without the computer* [italics added], once they had used RelLab. (p. 85)

This observation shows the power of an interactive visual display to convey otherwise extremely abstract ideas, and implies a similar potential for MBL experiments.

Roth, Woszczyna and Smith (1996) studied Year 12 students using Interactive Physics™, a simulation for mechanics and kinematics, to address the questions: How does the computer facilitate (or hinder) student-student science talk and group sense making? and, What are the roles of the computer display in this, and in the social construction of knowledge? The authors had noted that most previous studies focused on cognition independently of the social and physical setting of the students. Further, they drew attention to the role of conversation and reference to scientific symbols, diagrams and graphs in scientists' sense-making processes. They studied the interactions of students and computer in an approach known as symmetric anthropology, otherwise referred to as actor-network theory (Lee & Brown, 1994), by which both humans and machines contribute to the social and cultural atmosphere in which learning is shaped. One strand of the 11-week study involved forty-six Year 11 students in groups of three to five, operating a simulation which made considerable use of line, arrow and vector symbols. The methods of data collection and analysis used in this study revealed the scope for learning in fine detail the interactions of students and computer. Videotapes of three one-hour sessions were transcribed and subjected to conversational analysis and student behaviour analysis.

Roth et al. (1996) found that the physical presence of display symbols facilitated coherent conversation by providing an anchor for conversational topics, raising the computer display above the status of "just another visual aid." The monitor symbols were woven into and shaped students' sense-making activities. Students coordinated their meanings by pointing to specific symbols and agreeing on common understandings. Additionally, students coordinated drawings of familiar physical objects with screen displays picturing force and velocity arrows. As to whether students made connections with real-world events when using this simulation remained uncertain. In this respect an actual experiment using MBL sensors in association with the screen display would more likely contribute to such linkages.

However, difficulties were encountered as up to five students shared one computer. The lack of physical space and unequal proximity to the monitor curtailed interactions and attention. This researcher sighted few studies of the size of groups which best support collaboration. Hennessy et al. (1995) found that same-sex pairs or ability-matched triads were more effective in a 'Conceptual Change in Science' simulation. Clark and Jackson (1998) noted that with more than three students seated at an MBL computer, one or two lost focus and apparently learned little, leaving the thinking work to the two near the keyboard. These findings suggest that two students per monitor is optimal, and three maximal. Cox and Berger's (1985) study of group size concurred with this, and added more importantly the need to provide time for students to react with each other, as well as with the screen. In line with this Roth et al. (1996) wrote, "the important aspect of our finding is that it is less important who actually gets to manipulate the computer than whether the visual interface supports the interactions" (p. 1007). As distinct from simulations, MBL methods depend less on keyboard control, but rather decisions more often result in adjusting the experimental apparatus and repeating the experiment. Consequently control is more diversified and less likely to reside in the student controlling the keyboard.

Another constraint in the study by Roth et al. (1996) was that students' lack of experience with the software distracted from their simulation activities. Instances arose in which students interpreted vector symbols differently from that intended by the developer. Unless picked up and corrected by the teacher, students may embed unscientific conclusions into their reasoning. Even after four hours using the interface, students' awkwardness with the software limited their capacity to execute their decisions. MBL applications should also be approached with the same caveat: Unless the visual display is easy to manipulate and interpret, its use may be counterproductive to the learning it is designed to facilitate.

The MBL study by Kelly and Crawford (1996), reviewed earlier, reported on the interchange between students and display, and how computer representations entered students' conversations. A similar study was conducted by Lidstone and Lucas (1998), to analyse post-graduate students' styles of engagement with an interactive multimedia program (IMM). Five pairs of students were videotaped using an IMM, also during focus group discussions about their experiences. The purpose was to understand how students would approach interaction with the IMM program, which comprised an introduction to ethnography. This study revealed a range of different modes of engagement between students and the display. These were: (a) independent interaction, in which each student related to the monitor with little evidence of communication between one another; (b) independent interaction, but with efforts made by one (or both) to accommodate the agenda of the other; (c) cooperation to the extent of negotiating control of the program, with some discussion of each one's agenda; (d) mediated collaboration, in which students followed a common agendum, where their interactions were initiated and sustained by the display; and (e) reflective collaboration, similar to mediated collaboration, in which extensive discussion made little reference to the computer. As students became more proficient with the software their interactions and engagement with the content of the material increased.

Lidstone and Lucas (1998) noted that learning to use the software took precedence over intellectual engagement, and that instructors need to consider the composition of groups and how to assign tasks that maximise student-student-computer interactions. Similar findings have been noted with MBL experiments. However, it is speculated that less sophisticated and younger students, in longer established friendship groups, would be more inclined to interact, especially in the setting of a science laboratory.

Studies of simulations and multi-media show the computer monitor effectively promotes small group collaboration as students talk meaning into symbols. The graphic symbols can be retained mentally and drawn on to assist in reasoning processes at later times. Students need the support of an uncomplicated software protocol and appropriate teacher supervision. However, to date many questions remain unanswered about the nature of human interactions and construction of meaning by students using simulations and multi-media.

2.3.2 The display as actor and medium for learning

Many studies of computers in science instruction accord the instrument no more than the role of a tool, certainly not that of a participant, as are the students (McLellan, 1994). For example, Tao and Gunstone (1997a) investigated the conceptual changes in science made by Year 10 science students through collaborative learning at the computer. Pairs of students used physics simulations in settings intended to generate cognitive conflict, and the researchers investigated aspects of collaborative learning that fostered conceptual change. Tao and Gunstone arrived at their conclusions without recourse to the contribution of the display as a legitimate group member. The computer was not viewed as participating in the collaboration process. While acknowledged as part of the context, the moment-by-moment contribution the computer made to the discourse remained sidelined.

There is however another approach, one that avoids the separation of human and technological elements. Bigum (1998b) reflected on the status of computers in schools in these words:

> Many discourses which frame computer use in schools are based upon a distinction between the human [teachers, students, administrators] and non-human elements [computers] of computer use . . . Actor-network theory avoids the separation of human and non-human elements by positing that for analytical purposes, no distinction needs to be made between the human and the non-human. (p. 3)

Roth (1996) used actor-network theory (ANT) to analyse “knowledge diffusion” in a primary classroom. He contended that “cognition arises from the interaction of the task, the individual, and the (physical and social) setting” (p. 184, parenthesis his). Each student, student belief, common knowledge, concept, theory, teacher, teaching practice, technology, monitor display, culture, dyad and class student body constitutes an actor, inter-related in a network which itself is an actor (Roth, 1996). ANT analysts recognise that learning arises from activities situated in the network, which in turn reflexively shape the actors and network (Lee & Brown, 1994). Roth defended ANT as the basis for a legitimate research methodology.

> In the past, this form of analysis allowed us to model phenomena such as . . . (b) conceptual change in science and science classrooms as a social achievement, and (c) the affordances of technologies in science classrooms as mediating agents in the construction of social and natural facts. (p.186)

If the status of the computer as medium can be so closely related to the learner that the human/non-human differentiation is removed, then the question arises as to how important the medium is to the learning process. Clark (1994) argued that the medium does not influence learning, only the instructional methods do. He contended that learning results from teaching methods. Clark claimed that no one medium can exclusively and demonstrably deliver learning gains, and that studies should differentiate between method and medium. "Over a period of 70 years, we have failed to find compelling causal evidence that media or media attributes influence learning in any essential and structural way" (p. 27). For this reason he called for a moratorium on media research until a "new theory" was developed. From Clark's view it was important to identify media that were "capable of delivering the method at the least expensive rate and in the speediest fashion. Media influence cost or speed (efficiency) of learning, but methods are causal in learning" (p. 26). Certainly it has been demonstrated already that MBL methods influence the efficiency (speed) of learning (Rogers & Wild, 1994; Stein, Nachmias, & Friedler, 1990).

Kozma (1991) argued along a different line, namely, that as students work with the medium they construct knowledge, and that methods and medium cause more or different learning depending on the particular medium (Berger et al., 1994). He noted that a medium might have a characteristic symbol system and processing ability that can connect mental representations to the real world, without which learning would not be facilitated. The key to instruction was that the instructor utilise the characteristics of the medium which the learners cannot provide for themselves, to bridge the real world and the symbolic systems integral to learning science. Kozma drew on examples from MBL (Brasell, 1987; Mokros & Tinker, 1987). The findings of Thornton and Sokoloff (1990), Weller (1996) and Mokros and Tinker (1987) showed that MBL could provide activities and visualisations of science concepts that are undeliverable by other media. Of educational technology, MBL is unique in its capacity to provide complex real-time symbols coincidental with physical events under student control. MBL could provide the example of a medium which influences learning using Clark's criterion of the "replaceability test" (Clark, 1994, p. 22). Kozma contended that Clark created an unnecessary division between method and medium. While some students will learn regardless of the medium, others will take advantage of the characteristics of the medium to help construct knowledge. Hence Berger et al. (1994) supported Kozma on theoretical and pragmatic grounds for continuing research on the use of technological media in science.

The studies reviewed in this section have illustrated the viability of videorecording students, and conversation and behaviour analysis, to study in fine detail student-monitor interactions. Actor-network theory provides a basis for removing the human/non-human barrier and introducing the monitor display as a group member which mediates social discourse. A number of lessons arise from this section, to optimise the use of the computer: limit group sizes to two or three students; use uncomplicated software that will not inhibit task activities or conversation; and allow students time to interact and interpret.

In view of the many positive contributions to student learning made by simulation and hypermedia activities (as reviewed in this section), the present research may provide persuasive evidence that the medium of MBL influences learning in a way not replaceable by another medium. This would be contrary to the claim by Clark (1994) that only the content and instructional strategies influence learning and motivation, and not the teaching medium.

2.4 PHYSICS INSTRUCTION AND LEARNING THEORY

This major section of the literature review relates to current learning theory and practices with a particular emphasis on physics instruction. This section will guide the philosophy underpinning the development of classroom teaching in the present study. The last few decades have seen a significant change to student centred learning based on a constructivist epistemology. Two aspects of this framework are examined: personal constructivism and processes of conceptual change, and social constructivism. Teacher difficulties with implementing constructivist principles of learning in the classroom are addressed by describing guidelines for conducting a physics MBL. Finally, a theoretical framework is established for engaging student interaction in the laboratory.

2.4.1 From structuralist to constructivist views

Western modernist science that has developed over the past four centuries has presented scientific knowledge as a representation of reality based on empirically grounded inductive reasoning. Science education has been typified by teacher-dominated classrooms, curricula not attuned to student views and experiences, laboratory activities prescribed for technical skill acquisition and to verify learned theory, and teacher as trainer rather than educator (Taylor, 1998). McDermott (1991) described physics education in US secondary schools to the 1960s as consisting mostly of reading and memorisation of facts from a course text, solving standard problems, completing a set of standard experiments, and preparation for examinations. Learning was a process of receiving teacher-transmitted knowledge based on an empiricist view of knowledge.

With the arrival of the space satellite age, new physics instructional materials were launched which prescribed not only a modern content, but also the manner by which it was to be taught. The intention was to engender activity and inquiry with innovative curricula. Many inquiry-based curricula were developed for school physics, including PSSC (Physical Science Study Committee) and Harvard Project Physics. In her review of the history of physics teaching in the US at that time, McDermott (1991) claimed these initiatives failed to a large degree, for two reasons. Firstly, teachers were inadequately trained to master teaching materials such as PSSC Physics and Harvard Project Physics. Secondly, the materials targeted above-average students. Research has shown that inquiry-based curricula failed to promote inquiry related higher-level thinking skills (Tobin & Gallagher, 1987).

Following the late 1970s, attention turned to re-thinking the epistemological and ontological bases of science education, notably in the fields of cognitive and social psychology. This new direction was reflected in the change from research in the mid 1980s about whether or not a certain procedure led to improvement in learning, to qualitative studies of the reasons for changes in learning outcomes (Duit & Treagust, 1998). McDermott (1991) reviewed the results of research in physics education over the twenty years to 1990 involving physicists, cognitive psychologists, and science educators. She found the most significant change in this period had been the focusing of more attention on the student adopting a constructivist philosophy of learning.

The ideas of constructivism were not new.

> Constructivism only arrived on the science education scene once it acquired a new vocabulary to match new intentions . . . much of the necessary language was to be found in Driver and Easley's memorable article in this journal [i.e., Studies in Science Education, 1978] which created tools for the accelerated rise of constructivism in science education. (Solomon, 1994, p. 3)

2.4.1.1 Constructivism as a philosophy

Constructivism can be viewed as a philosophical position (Matthews, 1997) on which constructivist teaching and learning is built. Whereas teachers who hold to an empiricist view of science tend to use traditional methods of imparting knowledge, those who adopt a constructivist framework see themselves as mediating classroom activities that provide opportunities for students to interact. Research shows that teachers find the epistemological conversion from traditionalism a difficult (Hand, Lovejoy, & Balaam, 1991; Hashweh, 1996; Huibregtse, Korthagen, & Wubbels, 1994) but some would say necessary one (Hardy & Taylor, 1997), if they are to use a constructivist approach to teaching.

The extreme philosophical position of radical constructivism (RC), as expressed by von Glasersfeld (Hardy & Taylor, 1997), is based on a number of core epistemological commitments, which can be expressed concisely: The laws of nature are not those of absolute reality, but mental constructions or inventions of individuals devised to make sense of observations; and, these constructions are shaped by the individual's interaction with other persons, groups or institutions. Constructivist ontology is largely realist (the world exists apart from our thinking about it), sometimes idealist (the world exists only as a product of our thinking). Either way, our knowledge of the world is what the individual makes of it, not what he/she is told about it (Matthews, 1993). Some educators such as Hardy and Taylor (1997) call for teachers to commit to this relativist epistemology, "for without such they are unlikely to be prepared to reconstruct their pedagogical practices . . . [to resist] the considerable momentum of tradition" (pp. 135,145).

Without doubting that teachers' beliefs determine how they implement science curricula (Tobin, 1990b), the degree to which the teacher needs to participate in the philosophical debate between realists and anti-realists is questioned by Nola (1997):

> Constructivists in science education often wrongly assume that the debate can tell us something about the teaching and learning of science. Constructivist teaching and learning is another matter, best contrasted with didacticism. However, it is commonly assumed that a realist account of science goes with a didactic 'tell it how

> it is' approach to teaching and learning while a non-realist account goes with a more personal constructivist approach. . . .[there are] misleading links between the two. (p. 57)

In this overview, the present researcher does not feel compelled to debate the philosophical or epistemological claims of radical constructivism (RC) made by the many commentators on constructivism. Some researchers take a strong stance for an antirealist view ("scientists invent not discover") (for example, Hardy & Taylor, 1997; Roth, 1994; Tobin, 1990b), others for a relativist view ("scientific 'truth' is problematic") (Collins, 1985; Latour & Woolgar, 1979). In distancing themselves from RC, Driver, Asoko, Leach, Mortimer and Scott (1994) found the realist ontology of Harré (1986), ("that scientific knowledge is constrained by how the world is and that scientific progress has an empirical basis, even though it is socially constructed and validated") was "a position we find convincing" (Driver et al., 1994, p. 6). To Driver et al. the important issue was this:

> The core commitment of a constructivist position, that knowledge is not transmitted directly from one knower to another but is actively built up by the learner, is shared by a wide range of different research traditions relating to science knowledge. (p. 5)

As a theory of learning, of how beliefs are developed, constructivism is a theory of the negotiation of meaning at a personal and at a social level, rather than the transferal of knowledge from one person to another per se. These two dominant contemporary traditions, personal and social constructivism, are now discussed in more detail.

2.4.2 Personal constructivism

From the personal constructivist perspective, learning science can be seen as an individual activity. Students are seen to construct their own knowledge based on prior knowledge and personal experiences with science activities. Their current knowledge schemes are modified to adapt to more complex experiences. Deep mental engagement is required as students construct new knowledge that is viable to them, and incorporate it in their view of the world.

Personal constructivism is closely and frequently identified with Piaget's view of knowledge construction (for example, Driver, 1983; Driver et al., 1994; Duit & Treagust, 1998). As the student assimilates or adapts to new sense impressions, he/she accommodates or restructures existing cognitive structures. The learning process requires mental application in a process of conceptual change. Knowledge is not transferred from teacher to student, but through the senses the student builds a model of reality, a personal construction that accommodates external experiences including interactions with the teacher. When confronted with new experiences the learner compares these with what he/she knows and resolves discrepancies in which a process of "equilibration" restores the balance.

Students draw on a range of "commonsense" knowledge schemes, which are rather specific in a number of domains. Some of these, in the areas of heat and temperature and displacement-time graphs, will be referred to later in this study. Though often adequate for daily guidance, unless modified these "commonsense" schemes may hinder students' scientific reasoning (diSessa, 1987; Driver et al., 1994; Duit & Treagust, 1998; Mokros & Tinker, 1987). Students may also possess multiple conceptual schemes, or different ways of thinking, and draw on a scheme depending on the context. The scheme drawn on to explain an event witnessed in a science class, and the scheme used to explain the same event at home may be quite different, even contradictory, and yet pose no apparent conflict for the student.

2.4.2.1 Processes of conceptual change

From the view of mainstream constructivism, conceptual change takes place within a person's head. Constructivist approaches from the late 1970s had as a key aspect conceptual change, the implication that students' prevailing conceptions (or misconceptions or alternative conceptions) needed to be exchanged or restructured or added, to accommodate new science conceptions (Duit & Treagust, 1998). Teaching for conceptual change may follow a number of pathways. One kind of instruction proceeds from the student's existing conceptions that are compatible with canonical science. Another begins with preconceptions that are incompatible with science, and leads students to reinterpret their understanding. A third constructivist approach deliberately employs cognitive conflict: conflict between students' predictions and experimental results; between students' and teacher's ideas; or between the ideas of different students (for example, Driver, 1989; Tao & Gunstone, 1997b). Students must necessarily see the conflict, and by a Piagetian process of assimilation and accommodation restore mental equilibrium, though what students and teacher see can be problematic. A fourth constructivist approach is to use problem solving as a learning strategy, by which students' understanding of their world is challenged. Teachers must have a clear idea of what students already understand so they can devise problems which will help students construct new meanings (Wildy & Wallace, 1995).

A problem with efforts at bringing about conceptual change is that exchanges rarely take place in their entirety, and old ideas are not extinguished but persist in particular contexts. Indeed in some contexts misconceptions are quite useful (Duit & Treagust, 1998), and explanations using such 'non-scientific' terms can avoid the pedantry which can alienate science from the real world. Conceptual change approaches hold that the aim of science instruction is not to dispense with everyday views, but to make students aware that in certain contexts scientific conceptions are more fruitful.

Posner, Strike, Hewson and Gertzog (1982; also Hewson, 1981) proposed a Conceptual Change Model (CCM) composed of two major components. The first was a set of four conditions for conceptual change: intelligibility, plausibility, fruitfulness, and the degree to which the learner is dissatisfied with a conception. The second component was conceptual ecology: the relationship a concept bears to factors such as other knowledge, analogies, previous experience and the learner's epistemology. The learner asks: Do I have reason to change, and can I live with the change? The theory draws analogies between conceptual development in science and in individual learners. This model was used to develop a framework of criteria modes representing intelligibility, plausibility and fruitfulness. Such criteria are precursors to conceptual change. The framework would give structure to any analysis of science classroom discourse. The criterion of intelligibility – can the learner express clearly his/her ideas? – rested primarily in the learner's ability to express the idea verbally, recall associated images, describe similar examples, and even use gestures or body movement to convey his/her feelings. Thorley and Stofflett (1996) suggest this framework can contribute to interpreting classroom discourse, and hence is relevant to the present research specifically by looking for evidence (or otherwise) of students making intelligible their laboratory experiences.

Tao and Gunstone (1997b) used the CCM in their research with Year 10 boys using force and motion simulation software. The CCM proposes that there are two patterns of change. Assimilation is about using existing concepts to understand and explain new phenomena. Accommodation involves the considerable change of rejecting or rearranging existing concepts in the light of new experiences. The learner has first to accept that the new conception is more elegant than the existing one before changing concepts.

Tao and Gunstone (1997b) then drew attention to a number of additions, variations or alternatives to the CCM. Motivation and the classroom context may also contribute to conceptual change (Pintrich, Marx, & Boyle, 1993). Change, by accommodation, may not be immediate but rather incremental. Different concepts may be held for different contexts, existing in parallel, each useful for its own particular application. They then discussed a number of recent and more detailed taxonomies of conceptual change.

During the course of the simulations, Tao and Gunstone (1997b) sought to present to the students discrepant events which might induce cognitive conflict, leading to reflection, and reconstruction of their conceptions. They found that conceptual change was a slow process, making long-term change extremely difficult, particularly if conceptual changes are to be applied to new contexts. Two contexts in the present MBL research will be (a) the physical experiment (a component not available in a simulated experiment), juxtaposed with (b) scientific symbols graphed on a monitor. Aspects of the results of this study will build on those investigated by Tao and Gunstone.

The initial theory of Posner et al. (1982) strongly emphasised the appeal to logical argument to foster conceptual change. The metaphor of student as scientist played a key role in the initial theory. Duit and Treagust (1998) question this metaphor as an aid to understanding students' conceptual change. The learning contexts of scientist and student differ significantly and attain to different ends. The theory also neglected affective (relating to student interest and motivation) and social issues that also play contributing roles in conceptual changes. However, the four conditions of Posner et al. provide useful explanations as to why conceptual change is so difficult. If a preconception is deeply rooted in experience and has proven successful in daily life, then there may be no dissatisfaction with the conception. If, due to a lack of background knowledge, a new conception remains unintelligible and hence implausible, then conceptual change may again be hindered.

Complementary to conceptual change is the idea of conceptual growth, whereby a student's everyday conceptions are not necessarily the explicit starting points of instruction. Learning may start with the student's general thinking schemata, and by the use of analogies he/she is led to the intended concepts. In their account of learning processes, Duit and Treagust (1998) remind us of the many and complex pathways to conceptual growth or change, which Tytler (1994) considers are only useful when applied to student cohorts and not for general insight into individual construction of understanding.

In describing conceptual changes in the adolescent, Linn and Songer (1991a) assert that the process of knowledge acquisition begins with actions and observation. The unreflective "action knowledge" gained from these experiences is a set of simple conclusions. Through reflective abstraction, action knowledge from various experiences is combined into "intuitive conceptions," to explain in more generalised ways the events they observe. Teachers providing multiple representations of the same idea can facilitate the process. Linn and Songer hypothesised that effective instruction enables students to integrate the intuitive conceptions drawn from different domains into broader "principles" such as are held by scientists. Should the domains of knowledge to which students are exposed become too narrow (for example by over-specialisation in a crowded curriculum), or if instruction develops concepts in isolation, these ideas may not be integrated. The students risk abandoning their view of science as "making sense" to that of "facts to be memorised." Sufficient time for reflective abstraction is necessary for the sound construction of guiding principles that are not easily challenged or forgotten.

To amplify this view of conceptual change, Linn and Songer (1991b) developed a 14-week MBL and simulation course in thermodynamics for Year 8 students called "Computer as Lab Partner." The application of theory to practice proved to be lengthy and challenging, and the coursework underwent a number of adjustments in instructional techniques. In the fourth version of this program the students used a predict-observe-explain (POE) approach along with real-time graphing of experiments. The observation condition induced students' active involvement. The requirements of prediction and explanation also induced motivation, reflection and integration of concepts. Linn and Songer considered that their extended efforts to apply learning theory in an MBL setting succeeded on a broad range of goals. They found students underwent a progression of understanding, from action knowledge to intuitive conception to scientific principles. There remains a controversy as to the cognitive mechanisms responsible for such changes. Posttest results and interviews showed that students persistently leaned towards simplified (often incorrect) explanations, and few attained the integrated understanding of experts in the examples of thermodynamics covered in the course. This was despite the curriculum coursework (originally of one week's duration) being expanded to fourteen weeks. An alternative methodological approach would have been to focus on the interaction within and between groups. Some analysis of discourse by Linn and Songer may have provided some insight into these questions.

2.4.2.2 Thought processes during instruction

This section reviews some cognitive models of learning which can provide the teacher with assistance to understand what is going on in students' minds as they learn. The models provide support for many common teaching practices, and suggest fruitful avenues for trying new teaching techniques. Of concern to this study is the potential to relate these models to learning processes in the MBL. These models also expose the difficulties of understanding in depth how students think.

Nakhleh and Krajcik's (1993) investigation of students' thought processes during laboratory work used a theoretical approach founded on three models. The first was a model of cognitive structure, the generative learning model. This supposes that learners generate their own meaning from instruction, based on their background, attitudes, abilities and experiences. The learner selects information to be assimilated, draws inferences from stored knowledge, then stores newly linked meanings back in the knowledge base. Learning is thus viewed as a generative learning model and as a cyclical process.

The second, a model of cognition, was based on that of Ericsson and Simon (1984), which describes how learners process information during an activity. The information can be stored for a short time in several sensory memories. The information can be stored as well in the short-term memory (STM) during which it may or may not be drawn on for verbalisation and further processing. Information can be transferred to long-term memory (LTM) which has a very large capacity and will hold information relatively permanently. However, LTM has slow input and retrieval times. The mind is likened to a central processor that draws on and stores responses in STM.

The third, a model of concurrent verbalisation, suggests that information being processed in STM is available for verbalisation. Information can be stored in LTM, and retrieved to STM for further processing. The information currently stored in STM can be accessed by the researcher by audiotaping students' speech during their activities. During instruction students are actively engaged in retrieving knowledge from LTM, modifying and extending concepts, and generating increased comprehension.

Nakhleh and Krajcik (1993) used structured observations as a research strategy to determine if students do learn by a generative learning model. This required simultaneously videotaping and audiotaping students to obtain a record of their actions and verbal commentary. Students were prompted to "think aloud" during laboratory work. (A review of their findings appeared in section 2.2.3.) The transcribed audiotapes were analysed and coded as procedural, observational and conceptual (drawing conclusions or predicting) statements. These were compared to their actions at the time as seen on the videotapes. The frequencies of each code were calculated for each group at their particular experiments. Sometimes students failed to verbalise simple procedures, such as writing down data, whereas they verbalised the process of entering data on a computer keyboard. Groups using MBL had the lowest frequency of conceptual statements (the other groups were using pH meters and chemical indicators). Yet on closer analysis it was evident that the conceptual statements of MBL groups were more meaningful.

The structured observation technique was valuable in determining the focus of the students' observations. This was taken to mean that students' speech "indicated what information was being attended to and processed in short-term memory" (p. 23). In the case of students using pH meters, observational statements indicated they were focusing on a needle movement and two displayed numbers. They recorded fewer conceptual statements. The researchers contended "this burden may have exceeded their memory capacity, and prevented them from speculating" (p. 23). In the case of the MBL groups, the students "had a relatively low demand placed upon their short term memory because the microcomputer displayed the graph as it was being formed" (p. 24). The MBL groups sometimes 'raced ahead' and made conceptual statements before attending to procedural matters. The researchers suggested the computer acted as an auxiliary memory. There was some evidence that students observed, integrated concepts, and repeated the pattern as suggested by the generative learning model. Of the code sequences that were analysed, 29% used procedural-observational-conceptual statements for every lesson, which was consistent with the model.

Aspects of the videotaping/audiotaping technique recommend it as a tool for probing the thought processes of students in the present research, to the extent that a student's speech, actions, and focus of attention from moment to moment can be relied on to reveal his/her patterns of thinking. This technique may be made more robust by collecting student data using stimulus-recall interviews shortly following the videotaping of laboratory sessions.

White (1988) presents another model of students' thought processes, drawing on information processing and constructivist theories. The model begins with the learner's sensory perception of events. Perception is a function of attributes of the event such as intensity, attributes of the observer such as alertness, and the interaction of events and observer. In the latter case the observer filters and selects the events for perception. A selecting method is to group events into patterns, and in later school life this becomes very important in science. Knowledge of patterns is drawn unconsciously from long term memory (LTM). Knowledge from LTM also affects what sensations are selected. Different students, exposed to the same sensations, may select differently, to the frustration of teachers.

Events thus selected are stored in short-term memory (STM), and related knowledge recalled from LTM. White refers to experiments which showed that most people could store from three to as many as nine events contiguously in STM. Events can be chunked if one has the knowledge to do this, and one aspect of learning is to concatenate more information into single entities. The teacher breaks knowledge into a smaller number of meaningful units than a student does. What to the teacher is a simple statement of four connected phrases may to the student be a memory burdening connection of eight words, and the same applies to diagrams and other text. STM is overloaded and unless learning slows down the student cannot chunk the information. If the number of things to be kept in mind at once exceeds STM capacity, the problem is difficult. The successful student is one who has developed strategies for chunking. The duration of information in STM also affects learning. The time is difficult to measure, and is a function of rehearsal, nature of the item (a shape may endure longer than a word), and incoming of fresh sensations.

Information in STM can be processed further in LTM, if the student sets a goal, has the capability, and the time. The processing of a proposition includes associating meaning with its chunks, linking with previous knowledge, evaluating its validity based on prior knowledge and experience (with possible rejection). If the proposition is more intelligible, plausible and fruitful than earlier knowledge then it may be retained; but if the former proposition originated through experience, it may persist. The processing of skills, common in science, may be mastered without reference to the wider body of knowledge. Only by breaking the skills down into constituent propositions to be processed, does the skill take on full meaning. An episode can be a single event or a sequence of events. Episodes are remembered by how they are chunked and preferentially selected, which accounts for students seeing an experiment and describing its salient features in different ways. Science learning involves processing images. As with other memory elements, images are linked events. However, White notes that of the little research into images, most has been concerned with the effect of diagrams on recall of verbal knowledge.

White's overview of the thought processes during instruction concludes by listing levels of student attention. These range from not selecting an event, storing in STM, some processing, to deep processing with much linking to related knowledge.

Working memory (Pennington, Bennetto, McAleer & Roberts, 1996), as distinct from STM, refers to the ability to keep information in mind until some action can be initiated. There are three components of working memory, namely: (a) capacity or concurrent storage and processing; (b) maintenance of information over time; and (c) vigilance or level of activation, that is, a level of alertness maintained over a specific time period. These aspects of working memory – capacity, maintenance over time, and vigilance – may interact with each other. They may also be separable defining features that are differentially assessed in different tasks (Sun, 1998). A number of researchers have attributed the advantage of MBL real-time graphing to its relieving demands on students' working memory (Linn et al., 1987; Linn & Songer, 1991b).

> Since working memory has a limited capacity and retention time, the simultaneous presentation of event and graph "makes the most" of the cognitive facilities available. This should make it easier to transfer the event-graph unit (already linked together) into long-term memory as a single entity. (Beichner, 1990, p. 804)

Other researchers have made general observations about students' limitations of mental processing capacity that can frustrate learning. "At times, the students spent more cognitive energy on performing the experiment than on learning the physics. This was especially true when microcomputer-based labs were used" (Clark & Jackson, 1998, p. 1).

Another view of how individual students learn is the relational perspective taken by Prosser and Trigwell (1999). They argue that when students function within a given learning context, which includes teacher, fellow students, and their physical surrounds, the students form certain perceptions of their learning situation. Individual students become more aware of certain aspects of their context and less aware of others. Students systematically relate what they focus on both to previous learning experiences in similar topics, as well as to how they approach their present studies, which consequently affects their learning outcomes. This relational perspective has developed from studies of student learning at the tertiary level, and does not add to the present research.

From the individual constructivist perspective, learning is seen as a process of constructing knowledge internally, and tested through interaction with the outside world. From the cognitivist, or information processing perspective, sensory data comes to the student from the outside, is stored for a short time, processed internally, then either output or reserved in long-term memory.

2.4.3 Social constructivism

However, learning also embodies external social processes, as becomes evident when students talk about their ideas to one another. From this view the social context takes on an important meaning. Conceptual change approaches that centre on students' learning neglect the role external social influences play on their construction of knowledge. Marton (1986) developed a phenomenographic approach that characterised conceptions as reflecting person-world relationships (Duit & Treagust, 1998). Conceptual change takes place as individual students realign their relationships with their social and physical surroundings.

These ideas are developed within the social constructivist approach, which identifies with Vygotsky's belief that individual reasoning and development come from collective interaction (Davydov, 1995). Vygotsky theorised that children's development requires personal activity, in association with peers and guided by their elders, in their passage through life's changing social situations.

2.4.3.1 Learning science as a social activity

From the social constructivist perspective, learning is regarded as a social activity, in which students are engaged in constructing meaning through interactions with their world. Meaning is constructed when students discuss, explore and compare their ideas with one another. Students construct knowledge as they share problems and tasks and engage in social discourse. One facet of students learning science includes opportunities to 'talk science.' A measure of students' understanding of science is their capacity to engage in meaningful discursive practices (Duit & Treagust, 1998; Lemke, 1990). By engaging in such practices students are socialised into the cultural practices of the community, undergoing a period of cultural or cognitive apprenticeship (Rogoff & Lave, 1984). In the science classroom and laboratory expert guides (the teacher, more skilled associates, instructive tools and facilities, and even textbooks) afford novice students opportunities as they are introduced to the culture of science. Such classroom settings are far removed from those of practising scientists, so effort is required to provide settings for collaborative inquiry that approach those of the scientific community. Authentic learning situations as described by Roth (1995) are typified by open-inquiry classrooms. Closely related to cognitive apprenticeship and authentic learning situations is the idea of situated cognition. The activity in which knowledge is developed is seen to be inseparable from the process of learning.

Driver et al. (1994) argued that these views of learning are not prescriptive of pedagogical practice, but do suggest desirable teaching practices to teachers. One role of the teacher is to create interesting individual activities and an active social setting for the pupil. The teacher is to introduce new ideas and tools where necessary, and guide pupil activities. Listening to, and interpreting, their activities shapes further action.

With regard to social influences on learning, Solomon (1987) maintained "it is almost as though we do not understand what we think unless we can discuss it and receive back the effects it produces when our friends respond" (p. 63). Whether commencing school, or a new topic in science class, each child enters with a set of mental dispositions that are in part a product of his/her social background. These ideas that they have talked about and heard talked about, with which they sit rather comfortably, are structured quite differently from school knowledge. In the science class new ideas are introduced and discussed, and the meanings students give to these concepts are very much the products of social interaction. During adolescence the social context takes on a larger role in learning (Solomon, 1987). Science students begin to encounter new phenomena quite outside their former experiences. Students of this age are exposed to previously unstudied experiences, and are becoming more adept at abstract reasoning. Social awareness is more pronounced and has a stronger impact on their educational attainment (Linn & Songer, 1991a). This approaches the age range when students start to study physics.

If learning is seen largely as a social activity, then do students always benefit by group interactions? Solomon's review (1987) of research into interactive aspects of school learning noted that advantages of learning within groups were ambiguous. For example, some studies of the ability structure of groups (Webb, 1984) have shown that benefits accrue more to groups with a range of abilities – in which the more capable students tutor the less able – while middle ability students are neither advantaged nor disadvantaged. Group members may show a range of dispositions including consensus and domination, involvement and disengagement. In other studies, transcripts of conversation showed some groups gave mutual recognition to each other's ideas, while other groups expressed a lot of independent assertions with little mutual accommodation.

Solomon's review (1987) of the social influences in learning science provides a starting point for developing a methodology and analysis of discourse of student-student-computer interactions in the MBL. What are appropriate ways to study learning in these social situations? Research of a generation ago looked for statistically significant differences between treatment and control groups to study learning outcomes, and ascribed variations between individuals contributed to measurement error. Reasons why learners differed were not considered, nor the differences which contributed to these variations (White, 1988). A different kind of analysis is required in order to study socially situated learning.

The social-constructivist perspective on learning science places an emphasis on creating classrooms or laboratories characterised by students talking science. This has resulted in changed class/laboratory organisation (Arzi, 1998; Roth, 1994), teaching methods (Brna, 1991; Hand et al., 1991; Minstrell & Stimpson, 1992), and subsequently research methodology (Goodson & Mangan, 1996).

2.4.3.2 Collaborative learning

In physics instruction few teachers expect their students to be another Einstein who, as a young patent clerk, wrote his three famous papers of 1905 in virtual isolation. Ethnographic and sociological analyses show that scientists generally collaborate, and scientific theory is built by the incremental collection and integration of collectively shared knowledge, punctuated occasionally by bursts of individual or collective creativity. Scientists discuss, argue, compromise and negotiate meaning. For the most part, scientific work is characterised by (a) the production of visible displays that represent phenomena at a middle-level of abstraction, and (b) the interplay of mental comparisons or metaphors drawn from previous experience to build explanations (Roschelle, 1992). Scientists learn by collaborating.

Contemporary thinking about instruction in school science reflects this same paradigm of collaborative learning. Bruner (1985) described the mechanism of collaboration as "scaffolding" by the more expert peer, and "appropriation" by the less expert peer (Hickman, 1994). Piaget tended to see collaboration as producing individual cognitive conflict – disequilibrium. The learner adjusts his or her knowledge structure to resolve the conflict or to adapt to the new information, a process called equilibration (Driver, 1983). Roschelle (1992) argued for another process, that collaboration leads to a mutual construction of knowledge or convergence. Students gradually refine their concepts through an iterative cycle of displaying, confirming and self-correcting meanings of words, symbols and ideas. Evidence for this is drawn from conversational analysis (McHoul, 1980).

Alexopoulou and Driver (1996) studied high school groups of two and four, using analysis of discourse. The students discussed their answers to a set of written physics problems. The students' performances in physics reasoning and their modes of social interaction were less constrained in groups of four. They found that more often in groups of two, a student would be inhibited from speaking up to avoid social conflict, and this regulated the quality of their discussions. One of the problems with this study seemed to be the lack of rich stimulating material to generate more grounds for discussion and conversational interaction. A laboratory setting with multiple data representations may have provided a richer setting. This was evident in the research by Tao and Gunstone (1997a), as they studied the conversational interactions of dyads using a physics simulation program. They found that those students who maintained high on-task engagement, reflected on and reconstructed their concepts, underwent conceptual changes. Rochelle (1992) also used a science simulation setting, in a study that traced how two students reached a convergence of understanding that was quite different from their initial ideas of motion. The study by Kelly and Crawford (1996), reviewed earlier, revealed how understanding is mediated not only by students collaborating, but also by the laboratory environment and instrument displays.

Constructing shared knowledge involves more than social interaction; it also takes into account the context of learning (Duit & Treagust, 1998). Only by considering social actions in relation to the embedded situation of learning can the mutual construction of knowledge be understood (Roschelle, 1992). The present study is concerned with how students learn collaboratively within the context of an MBL.

2.4.4 Teacher difficulties with constructivist teaching

Teacher attitudes to changes in teaching practices are important considerations. Sparks' (1983) synthesis of research in this area suggested that teachers are more likely to adopt a new practice when it is presented clearly with specific techniques for implementation. Further, teachers must be convinced that the innovation is worthwhile (from both their view and that of the students), and the result outweighs the effort. In a later study by Sparks (1988) she recommended that teacher in-service programs need to consider teachers' philosophical acceptance of a new strategy, by incorporating discussion of the positives and negatives, testimonials from users, and relating the theory underpinning the innovation. In the spirit of this advice this section reviews some of the difficulties associated with implementing a constructivist approach to teaching and learning.

In their study of physics teachers' conceptions of learning, Huibregtse, Korthagen and Wubbels (1994) found that experienced physics teachers in the Netherlands mostly used methods by which they had learned or preferred to learn. Based on a survey (n=113) and interviews (n=10) they found that many physics teachers persisted in believing "efficient learning is realised when teachers try to transmit knowledge" (p. 558). Imbued with the wonder and power with which physical principles can explain diverse phenomena of the world around us, teachers were often surprised at research that showed there were frequently significant differences between what they thought students learned, and what was actually learned. In these circumstances teachers need to reassess their epistemological approaches to teaching.

Researchers have found that, notwithstanding many teachers' commitment to constructivist teaching, the results have not matched the ideals or expectations. For some teachers the problem appears to be one of insufficient class time to cover an obligatory content in preparation for examinations (Geelan, 1995; Tobin, McRobbie, & Anderson, 1997). Teachers are also aware that a constructivist approach is not best received by all students (Tsai, 1999).

Strong support for traditionalist pedagogy remains. The physics teacher in the case study by Wildy and Wallace (1995) reverted from constructivist to traditional teaching methods due to social and cultural pressures within his school. The results of this study suggest that the case for transmissionist teaching rested on pragmatic rather than educational grounds. The school community in the study had an agenda whereby studying physics was only a means to an end. "The main consideration of Mr. Ward (the teacher) is to prepare his students for entry to university study" (p. 151). In the words of Mr. Ward:

> Lots of them won't do physics [after school], but most of them will be at university. Most students who do physics are doing it to keep their options open and the options involve courses requiring knowledge of formal physics and those requiring TEE [university entrance scores] of a certain level. (p. 151)

In the experience of the present researcher, only a minority of students chooses to study physics, not as a foundation for further studies, but because of the strong weighting contributed by physics results towards gaining university entrance. Wildy and Wallace were prompted to conclude: "We argue for a broader view of good science teaching than that proposed by the constructivist literature, one that takes into account teachers' and students' understandings of science in relation to their social and cultural contexts" (p. 143). Taylor (1998) cautioned: "Although an ethic of emancipation might enable constructivist teachers to enhance some students' learning, it is likely to affect adversely students who are committed strongly to a well-established objectivist epistemology and who are buoyed by an accompanying sense of well-being as passive-reception learners" (p. 1118).

Commitment to educational constructivism requires that teachers make pedagogical changes (for example, Hand et al., 1991) that flow from a prior acceptance of a constructivist epistemology. "Teachers need to be empowered with rich understandings of philosophies of science and mathematics that endorse relativist epistemologies; for without such they are unlikely to be prepared to reconstruct their pedagogical practices" (Hardy & Taylor, 1997, p. 135). The authors acknowledged, with respect to teachers adopting radical constructivism as a referent for their teaching, the presence of a "considerable momentum of tradition" (p. 145) to maintain an objectivist view of science.

Matthews (1997) addressed the question of the efficacy of a constructivist pedagogy in teaching science. Firstly, he noted that research on alternative conceptions had failed to give clear advice on how to teach different topics. Secondly, if knowledge is a matter of personal construction, how can children "come to knowledge of complex conceptual schemes that have taken the best minds hundreds of years to build up?" (p. 12). Thirdly, how does one teach areas of science that are largely abstract, removed from experience, unconnected to prior conceptions, and alien to common sense? In the latter case Matthews refers to atomic structure, and by inference to areas of science more likely to be studied by older students and not younger pupils. How this knowledge can be taught without conveying something to students is the problem raised by Solomon (1994):

> Constructivism has always skirted round the actual learning of an established body of knowledge . . . [students] will find that words are used in new but standardised ways: problems which were never even seen as being problems are solved in senses which need to be learnt and rehearsed. For a time, all pupils may feel that they are on foreign land and no amount of recollection of their own remembered territory with shut eyes will help them to acclimatise. (p. 16)

Some of these concerns raised by Matthews and Solomon were addressed when preparing laboratory activities and teaching materials for the data collection stages of the research. Driver et al. (1994) state clearly "if teaching is to lead students toward conventional science ideas, then the teacher's intervention is essential" (p. 7). Otherwise the student is left to discovery learning, which is ineffective or even detrimental for lower ability learners (Snow & Yalow, 1982).

2.4.5 MBL as a 'constructivist tool'

The MBL has unique aspects that support laboratory activities based on a constructivist epistemology. From this viewpoint the MBL is referred to as a 'constructivist tool.' Some features of MBL that can be used to support a constructivist framework in the laboratory are listed.

1. The monitor display (a) provides immediate graphic feedback, and multiple graph displays, which are conducive to engaging students in deep thought and discussion; (b) provides an enduring 'time history' of the experiment that supports memory demands; (c) provides a concrete image of abstract concepts; and (d) exposes students to symbolic realities such diagrams, charts and graphs.

2. By reason of its time efficiency, students are able to plan and control 'what if' experiments which can generate or help resolve cognitive conflicts. Small groups of students can use the additional time redeemed from traditional graph-sketching to predict, reflect on, discuss and explain what they have learned.
3. MBL can expose students to new and interesting activities often unavailable in a traditional laboratory.
4. MBL facilitates experimenting, and collecting and displaying data, that may provide the four requirements (Posner et al., 1982) theorised for conceptual change to occur: dissatisfaction with current conceptions, and making new conceptions intelligible, plausible and fruitful.

The present research will combine the above features of the MBL with what is known about constructivist teaching and learning. The report of the research has the potential to influence physics teachers in their own laboratory practices.

2.4.6 A framework for engaging on-task interaction

The nature of interaction of students with each other and the computer display is central to this study. To stimulate interaction, group dynamics need to be given some direction and be attached to a sound theoretical framework. The following reviews show that when students are required to plan strategies, record observations, and reason their conclusions, more and better learning takes place.

Solomon et al. (1991) reported on the experiences of children in a year seven class who mimicked a series of displacement-time graphs by walking to and fro in front of a motion sensor. On the first occasion the children described the lesson as play. After five days, Solomon et al. found the results of a test for memory of the interaction and application of the concepts into new fields were disappointing. One term later the lesson was repeated with the same children completing a worksheet. They were tested five days later. Correct scores on this test were about 80% better than that of the first test. Doubtless the children carried over some learning from their first experience. A second teacher conducted the same experiment with a similar class divided into matched halves based on their academic records. The experimental group that used the worksheets achieved about 60% better.

The researchers concluded "that a more durable learning process took place when the worksheet was used" (p. 348). They theorised that tacit learning (how children moved their bodies to replicate graphs) is not committed to memory unless first it has been articulated, whether by speech or writing, at the time of the experiment. The responsibility of the physics teacher therefore was to "provide a framework and context for learning which goes beyond just letting their pupils play" (p. 349). Rogers and Wild (1994) conducted loosely structured research with high school physics students, and noted that the use of an "outline worksheet" by students provided "a clear framework for drafting the plan for the investigation and monitoring the development and progress of ideas" (p. 27). These worksheets seem to have been different from typical worksheets provided to students conducting traditional laboratory experiments. Well-structured worksheets have the potential to support scientific reasoning skills consistent with constructivist learning. They could include the statement of problems (Brasell, 1987; McLellan, 1994), tasks designed to provide cognitive conflicts (Tao & Gunstone, 1997b), and space to record planning, predictions, observations, analyses of data, diagrams and conclusions.

Research has shown that reasoning sub-skills of observation and prediction can be enhanced under suitable conditions in an MBL. One reason for the study by Friedler, Nachmias and Linn (1990) was to learn how students could best use their time while they experimented. Their one semester study involved Year 8 students (n=110) performing heat/temperature experiments. The students were assigned randomly into two groups, showing no statistically significant difference on an advanced progressive matrices test (the variables were not stated). One group was required to complete observation records of a series of experiments while the second group completed prediction records. Both groups completed final written tests of their observation and prediction skills specific to the experiment domain. An analysis of these tests showed that the observation group described what happened on the screen in more detail compared to the prediction group. Conversely, the prediction group better justified their predictions. The researchers concluded that the skills of observing and predicting could be learned in the MBL environment, by requiring that students complete observation and prediction worksheets during the experiments.

An associated study (Linn and Songer, 1991b) describes how prediction and observation components for MBL were added to worksheets, so as to increase students' cognitive demands and improve their scientific reasoning. In one version of the study a comparison was made of the results of emphasising prediction and observation as separate skills. In comparison with an earlier version of the study, both skills significantly improved students' abilities to integrate understanding of heat energy and temperature. In the next version of their study both skills were stressed to see if the combination had a greater impact, or whether they might overload students' processing capacities. To counter the possibility of a teacher improvement effect a student teacher took two of the four classes. In comparison with an earlier version of the study, results showed that both teachers were equally effective, and that the combination of observation and prediction skills was as effective as the prediction condition of the previous version. Linn and Songer hypothesised that the observation condition required active processing of the temperature graph display as it developed, and not just when it was completed. The prediction condition required students to combine feedback from past experiments with their overall model of thermodynamics and to monitor their ideas. Their investigation demonstrated that appropriately structured worksheets greatly improved the efficacy of the MBL activities.

To help students focus on specific events and probe their understanding, White and Gunstone (1992) described a procedure for using predict-observe-explain (POE) tasks. The predict-and-observe procedures were essentially those analysed by Linn and Songer above. The tasks may be applied in any educational context, though the present applications are made to laboratory science. POE tasks require firstly that students understand the nature of the event. Students are required to predict an outcome and justify it. Predictions may be asked from a set choice, or be open-ended. Prediction requires students to select principles or recall to mind prior examples that may illuminate the situation at hand. The justification requirement discourages guessing. Students then describe what they see happen, and reconcile any conflict between their prediction and the outcome. The cycle is then repeated either by following the next required prediction, or the student setting his or her own.

Tao and Gunstone (1997b) used a POE technique to study the process of conceptual changes in a Year 10 physics class of boys. The lessons were based on the *Force & Motion Microworld* simulation. A set of worksheets containing 46 POE tasks was designed to promote cognitive conflicts that might facilitate cognitive change. For each task the students were directed to

1. make a prediction about the consequences when certain changes were made to the program,
2. explain their prediction,
3. run the program to test the prediction, and
4. reconcile any discrepancy between the prediction and the observation of the microworld.

It was important that students understood the nature of the problem before being asked to make a prediction, and commit themselves by writing it down with supporting reasons. Each student then recorded his or her own account of the observations. By working at the computer and talking in pairs, students could reconcile any discrepancies between their predictions and observations. Talking about discrepancies revealed much about their understanding. This method of engaging students in science discourse provided an effective framework to promote student interaction and on-task activity, and of documenting the social construction of meaning in the graphs.

POE tasks are appropriate for MBL experiments for a number of reasons. Research (Friedler et al., 1990; Linn & Songer, 1991b) has shown the skills of observing and predicting can be learned in the MBL environment. Group discourse can be initiated and maintained by POE tasks, while still requiring that students write individual responses. The procedures are already known and do not have to be learned. The tasks are supportive of constructivist learning, and from the researcher's viewpoint provide an excellent record of personal thought patterns to complement audio transcripts of conversations.

A word of caution for the design of worksheets comes out of the study by Maor and Taylor (1995) of student groups exploring the data base *Birds of Antarctica*. Because of the nature of their inquiry (navigating a complex network of data files) the worksheets took the form of a booklet. As became apparent during the study, the booklet unintentionally gave implicit support to individualised learning, and an increased measure of teacher control of student activities. This ran contrary to the researchers' intention to encourage social aspects of learning. The implication here is that teaching materials need to be designed with considerable care to reflect as closely as possible the teacher's epistemological approach to instruction.

This discussion of physics instruction and learning theory has established a philosophical and theoretical basis for structuring the classroom experiences and teaching materials in the present study.

2.5 OBJECTIVES OF THE RESEARCH PROGRAM

This review of the literature has presented an overview of MBL research and a summary appears in Appendix 1. Many instructional benefits from using MBL technology have been established, and increasingly so over the last decade by means of interpretive studies of student groups interacting with the monitor display and experimental equipment. That the majority of physics teachers has not utilised MBL activities more widely may be due to a lack of awareness of the capacity of the MBL to improve students' learning.

From the theoretical reference frame of constructivism many of the positive research findings in support of MBL activities can be understood in terms of enhanced student-

student interactions about familiar and discrepant events portrayed by real-time data. However, little progress has been made in understanding how students construct meaning of physical phenomena in MBLs (Clark & Jackson, 1998). Rules for pedagogical practice are not spelled out by constructivist theory (Matthews, 1997). For a teacher to enhance laboratory procedures he/she needs to listen to students' speech and interpret their behaviour.

The purpose of the present research is to add to the fundamental understanding of how MBL activities specifically designed to be consistent with the constructivist theory of learning support or constrain student construction of understanding. The specific research questions of this study have been stated previously in section 1.2, and are reiterated:

In an MBL specifically designed to be consistent with a constructivist theory of learning:

1. How do students learn physics?
2. How do the materials and teaching strategies support (or constrain) student understanding?

More specifically, pertaining to the first question:

3. What are the patterns of interaction between experimental phenomena, computer display, individual students, collaborative groups, and the teacher?
4. How are students' negotiations of new understandings mediated by the computer display?

The study has as outcomes:

1. The personal reflections of the teacher as researcher on his physics instruction.
2. A systematic documentation of ways by which students work effectively (or ineffectively).
3. Specific details of how the teacher acts to facilitate learning.
4. The development of appropriate pedagogical strategies incorporating MBL activities that will likely catalyse students' construction of understanding.

CHAPTER 3: METHODOLOGY AND DESIGN

3.1 INTRODUCTION

This chapter presents a justification for the use of an interpretive methodology based on naturalistic inquiry conducted by the teacher as researcher in his usual classroom environment. This is followed by a description of the research design, a three part study of the researcher's Year 11 physics students as they experiment in an MBL. Finally, the data sources and analysis techniques are described and are illustrated by referral to the pilot study conducted in 1999.

3.2 METHODOLOGY

The framework for this research is suggested by the nature of the research objectives. These objectives arise from the researcher's own concerns with, and interest in, his own classroom teaching and the use of technology, and are an extension of his previous research on teacher uptake of MBL methods. The present inquiry is not concerned with comparing the effectiveness of MBL techniques with other instructional methods, which studies abound in the literature, and which are not informative as to how students learn while they experiment. It is concerned with understanding the nuances of student learning in an MBL.

The researcher is familiar with the confirmation-of-theory cookbook type of experiment aimed at students obtaining a precise answer as a measure of success of a laboratory lesson, which is consistent with a positivist approach to science instruction. However, for some years he has made a conscious effort to implement a constructivist epistemology in his classroom teaching and laboratory activities. Tobin (1991) has noted that a change to constructivism is not easy, and teachers might take in the order of two years to change routine practices based on the dominant paradigm of objectivism. To change requires reflection on classroom practices, which are intrinsically associated with student learning. This dual concern for his teaching, and understanding how students learn, requires teacher research founded on the selection of an appropriate methodology.

3.2.1 Interpretive research

This study will use a qualitative or interpretive research methodology. Spector and Glass (1991) draw attention to three features that typify such research: (a) The studies are conducted in their natural setting, (b) the researcher does not intentionally manipulate the subjects or the environment, and (c) the data collected are initially descriptive. Such research may be described also as naturalistic research. Other features that will become evident in the present study are: Relativism is the philosophical base; a priori theories and hypotheses are not used (having previously accepted that constructivism is adopted as a referent for the educational context); participant observation is essential; questions and assertions emerge from the data; and, the researcher reports on his subjective perspectives of the students (as well as himself).

Interpretive research is appropriate for a social constructivist learning context, which assumes students construct their own socially negotiated meanings, and of which the minute-by-minute and day-by-day processes are not revealed by quantitative research (Gallagher, 1991; Spector & Glass, 1991). The social setting of their learning experiences, which extends to the teacher, texts (written and graphic), experimental materials, knowledge background and prior experiences, are all influential in determining what and how students learn in the laboratory. Learning as a social activity has been discussed earlier in some detail (section 2.4.3) (Duit & Treagust, 1998; Solomon, 1987). In their discussion of theories of knowledge acquisition, Chinn and Brewer (1998) include social pressures as a factor that can initiate and influence changes in knowledge, and note that students may choose from differing knowledge structures theories that help them achieve greater status or other social goals. By attempting to understand classroom interactions, interpretive research seeks to describe and interpret specific teaching and learning events, then extend beyond this to help teachers better understand the nature of their work and the meaning they give to it. Ethnographic methods, “the craft of participant observation,” for the present study are discussed in the following section.

3.2.2 Drawing on ethnography

The research will draw on some of the methods of ethnography and discourse analysis, using constructivism as a referent. Ethnographical studies are based on the assumption that groups share a unique culture, the various parts of which are interdependent, yet forming a unique whole. Cultural standards influence group behaviour, hence it is important to understand the cultural meaning of behaviour. Language characteristics may be seen as a means of communication or as a manifestation of a particular culture, both within and between groups. Such studies may be described as the ethnography of communication, whereas a focus on the patterns of interactions of groups is holistic ethnography (Spector & Glass, 1991; Tesch, 1990).

Through interpretive explanations the ethnographic researcher attempts to foster an understanding of how members of a culture see their world, their reasoning and the causes of their actions, by placing them within their specific social contexts. Ethnographic studies gather multiple sources of data through fieldwork, and in particular using audiotapes and videotapes. Shimahara (1990) traces the development, from cultural anthropology, of ethnographic studies of schooling in the 1950s, and which came to be formally recognised by the late 1960s. Ethnography requires researchers not only to report the culture studied, but to be perceptive observers. Shimahara selects for discussion three aspects of an ethnographic paradigm for educational settings. The first locates the research in a context in which human behaviour is shaped by the surrounding cultural configuration. This suggests that the observer relate observations not only to the immediate setting, but also to the broader sociocultural milieu of the society. It also requires the observer understand what sociocultural knowledge participants bring to the setting being studied. The second is a qualitative orientation. Researchers are interested in sociocultural patterns of human behaviour rather than quantification of the occurrence and distribution of events. They also hold that participants define events according to their own understandings, rather than that of the researcher. Further, they are interested in the qualitative character of natural settings as opposed to artificial situations addressing questions posed by the researcher. The third aspect of the ethnographic paradigm avoids the linear sequence of quantitative research that commences with problem definition and hypothesis. Rather, research is viewed as cyclical, beginning with an ethnographic project, then asking questions (regarded as tentative hypotheses or assertions), collecting data, analysing, and refining the cycle. Shimahara discusses two views as to how questions and hypotheses are generated. A phenomenological approach to fieldwork generates hypotheses in the process of data analysis. The second approach focuses strategies of primary data collection that actively and consciously directs inquiry. Hypotheses are developed in the field, along a line of theoretical orientation derived from fieldwork and substantive theory in social science.

3.2.3 Drawing on discourse analysis

This study, as with much contemporary science education research (Crawford & Kelly, 1997; Kelly, Chen, & Crawford, 1998; Roth & Lucas, 1997; Tao & Gunstone, 1997a), draws on methods of discourse analysis. From the perspective of social constructivism, knowledge is constructed in a social setting as individuals engage in talk and activity with shared tasks. Speech and social interaction mediate learning. Peer talk may have cognitive and motivational effects. From a Piagetian view social interaction overrides a student's self-centred thinking (Driver, 1983) and provides opportunities to confront alternative points of view. For Vygotsky, first comes the collective activity (for example students working together in a laboratory), then the assimilation of the culture and its symbols (enculturation into scientific discourse and its system of graphs, diagrams and processes), and finally individual consciousness (an understanding of scientific concepts and principles) (Davydov, 1995).

How discourse can best be understood has been approached from two major directions. The first is process-product research, which measures how frequencies of various categories of class talk affect learning outcomes. This is used to determine which teaching processes are most effective, for example, to improve student achievement. The second, descriptive or interpretive classroom research, attempts to describe the processes of teaching and learning. Research reports from the latter are derived from transcriptions of audio and video recordings of students, and qualitatively analyse excerpts of actual conversations (Bleicher, 1994; Gallagher & Tobin, 1991; Nakhleh & Krajcik, 1993).

There is no single approach to interpretive analysis. The method used depends on the aims of the research. For example, in the present study the analysis must provide answers to such questions as: What are the patterns of interaction between the participants? How does the monitor display enter the discourse? What does the discourse reveal about students' use of concepts and thematic patterns? What is the contribution of the monitor display to students' understanding? Regarding the roles of the computer display in classroom discourse, Cazden (1986) stated:

> Computer terminals may thus become significant sites for research on peer interaction, a new context for the exploration of how the social and the cognitive connect. But such research will pose special problems for recording technology; it will be essential to see what the children are working with on the screen as we overhear their talk. (p. 451)

Interestingly, the phrase "interactive dialogue" is frequently used with student-computer communications (for example, Lazarowitz & Tamir, 1994, p. 101), though neither the user nor the computer engages in conversation. The phrase implies an exchange of ideas between two parties, mediated by keystrokes and display symbols instead of speech. Provided a reliable record of these interactions can be made, then the possibility exists of including the computer display in the discourse analysis.

3.2.3.1 Conversational analysis

Participants in a dialogue, if they are to reach agreement on an issue, must be able to guide each other's understanding or interpretations of what is being said. As discussed by Gumperz (1992) each speaker in a conversation looks for "contextualization clues," or speech signals that affect communication. Prosody includes accent, modulation, stress and intonation in speech. Paralinguistic signs include tempo, pausing, laughter, tone of expectation, gestures, or overlapping speech. The contextualisation clues that accompany a spoken phrase give it a situated meaning that overrides its basic lexical meaning. The inferences made by the listener are subconscious, such that they are difficult to elicit by direct questioning.

As a helpful analytic technique, contextualisation clues may be seen as affecting inferences at three levels. The first is the perceptual plane at which phrases are interpreted. This involves transitions and relations between phrases together with prosody. At this level conversation is managed into turns-of-talk, identifying new information, main points and secondary points. The second level is sequencing by which the listener interprets the "communicative intent" of the speaker. The third level is activity, the listener's expectation of what is to come in the conversation, about suitable topics to pursue and about the quality of the interpersonal relations. Gumperz transcribed speech in breath or intonation groups. These groupings were expressed naturally by the speaker, based on prosody, rhythm, and syntactic and semantic knowledge. The contextualisation clues were added by a transcription convention using a set of typeface symbols (see Gumperz, 1992). However, it should be stressed there is no single convention of transcription.

Conversation transcribed is usually ungrammatical and its meaning problematical, unless contextual clues are considered. Gumperz' analysis of a conversation (1992) between speakers of two different ethnic origins showed that speakers can approach dialogue with different contextualisation systems. Speech signals of students may be affected by their different ethnic, cultural and religious backgrounds.

Lemke (1990) provides a theoretical framework for the analysis of thematic content in students' discourse as they "talk science." The following is a summary of his approach and how it may be applied in the present study. A sentence consists of words or terms (thematic items) that are related. Words obtain meaning from the way in which they are used. The study of semantics helps describe how the meanings of two words or phrases are related when they are used together. The relationships between thematic items may be attributive, or may classify, quantify or identify one as part of a larger set, be synonyms or antonyms, give location, and so forth. Lemke equates these relationships to concepts. As little is known about brain physiology and the neurosciences, and since the process of "thinking" is only inferred by the speech, actions or writing of people, then Lemke "cuts out" mental concepts and analyses thematic patterns of language and other actions. Concepts do not exist outside of being constructed by our speaking or picturing, through words or signs; or being reconstructed from how someone else said something. Semantic analysis shows that the same concept may be expressed in a variety of ways, by employing different words and grammatical connections. To "understand a concept" means that a person is able to express the meaning of semantic relationships in different ways, using his/her own words.

A number of semantic relationships may themselves be related to form a thematic pattern. A thematic pattern is a way of picturing a network of relationships between the key terms in the language of the subject. The thematic pattern is the principal unit of science discourse. Thematic patterns can also be stated in different ways. For students to make sense of what is being talked about, they have to use thematic patterns. Students "make sense" of what they hear or read when they recognise a familiar thematic pattern. Even in dialogue they may "fill in" missing words from their partners' speech if they recognise the patterns.

A particular sentence may possibly fit different thematic patterns, depending on the context of discussion, or the cultural background of the speaker or listener. Consequently, two persons sharing a dialogue may interpret each other quite differently, a situation Lemke notes is not possible to avoid. One of the challenges of teaching is to elicit from a student the intended thematic pattern.

To give meaning to a text (that is, a long or short stretch of writing or speech), the student searches out the thematic meaning by making comparisons with already known thematic patterns. The student does this by looking for the same thematic items and the same pattern of semantic relationships connecting them (remembering that actual terms and grammatical constructions may indeed differ). Small thematic patterns may be condensed into a single term (a thematic condensation), and semantically linked to other simple or condensed items. Those concepts in science that are most difficult for students to grasp are thematic condensations.

Lemke equated scientific theories and conceptual systems with thematic patterns of semantic relationships. Thematic patterns can be found diversely in textbooks, a teacher's monologue or student dialogue. When students "talk science" in the laboratory they are gaining practice at expressing thematic patterns. Consistent with Lemke's view of concepts as being linguistic expressions, reasoning is primarily a way of talking – whether as private "inner speech" or talking to others. Reasoning involves combining thematic patterns with organising patterns, patterns of logic or scientific prose or argument. He noted that apart from language, which predominates, meaning making and reasoning also implicate the use of images, diagrams, formulae, body movement, writing and manual skills.

Aspects of Lemke's approach to semantic analysis are applied to the present research. Considering the problematic nature of understanding student discourse in the MBL, these procedures provide a framework for making sense of their "science talk." Semantic analysis may identify whether students understand concepts and make sense of their activities by recognising thematic patterns. It may reveal from where previous thematic patterns are drawn and new ones are created, and examples of thematic condensations and science language mastery. In particular, semantic analysis may clarify the contribution of the computer display to students' understandings.

Analyses of discourse vary in the level to which speech is dissected and meaning constructed. "Excessive attention to detail can be dysfunctional" (Misanchuk & Schwier, 1992, p. 370) if generalisations or trends are being sought. Decisions must be made as to which segments of a transcript bear more detailed study. Interpretive studies may work from transcriptions of whole sentences as spoken, annotated to indicate pauses and other actions (for example, Roth et al., 1996).

3.3 RESEARCH DESIGN AND METHODS

3.3.1 Design

A pilot study (see section 3.5) preceded the two main parts of this study, experiments in thermal physics and kinematics. The reason for conducting two parallel studies is discussed in section 3.3.6. The major features of the design are presented in Table 3.1.

Table 3.1

Major Features of the Research Design

	Pilot study	Part 1: Thermal physics	Part 2: Kinematics
Time	March 1999	Semester 2 1999	Semester 1 2000
Students	Year 11 class 1999	Year 11 class 1999	Year 11 class 2000
Prior activities	Prepare POE sheets. Students practise with kinematics hardware & software. Introduce new terms in kinematics.	Prepare POE sheets. Students practise with heat hardware & software. Introduce new terms. Teacher wears microphone.	Revise pilot POE sheets. Students practise with kinematics hardware & software. Introduce new terms. Teacher wears microphone.
During each MBL lesson	Three 70-minute lessons. Dyads experiment using worksheets. Select and audiotape/ videotape one dyad. Second fixed camera videotapes main laboratory. Teacher wears microphone.	Four 70-minute lessons. Dyads experiment using worksheets. Select and audiotape/ videotape two dyads and monitor display. Third fixed camera videotapes main laboratory. Teacher wears microphone.	Four 70-minute lessons. Dyads experiment using worksheets modified from pilot study. Select and audiotape/ videotape two dyads and monitor display. Third fixed camera videotapes main laboratory. Teacher wears microphone.
Post each MBL lesson	Photocopy notes of one dyad. Review the a/v-tapes. Interview dyad. Maintain teacher journal. Use each lesson to guide observations.	Photocopy notes of the two dyads. Review the a/v-tapes. Interview two dyads. Maintain teacher journal Each lesson to guide the future focus of observations.	Photocopy notes of the two dyads. Review the a/v-tapes. Interview two dyads. Maintain teacher journal. Each lesson to guide the future focus of observations.
Lesson after last MBL		Audiorecord teacher's follow-up lesson to discuss group activities.	Audiorecord teacher's follow-up lesson to discuss group activities.

	Pilot study	Part 1: Thermal physics	Part 2: Kinematics
At the end of each module	Transcribe and annotate tapes. Copy student notes, end-semester tests and computer data. Analyse and refine methods of data analysis. Formulate tentative assertions to guide the main study.	Interview groups not previously interviewed. Transcribe and annotate tapes. Copy student notes, end of semester tests and computer data. Analyse data. Modify the planning for part 2 in response to emerging understanding.	Interview groups not previously interviewed. Transcribe and annotate tapes. Copy student notes, end of semester tests and computer data. Analyse data.

3.3.2 Data sources

The research design of this study utilised a range of natural protocols to capture the lived experiences of two different classes of Year 11 physics students, each class experimenting in an MBL for four 70-minute sessions. The introductory and follow-up lessons to the MBL activities were also intrinsic to the study, and were audiotaped. During each MBL, data sources included annotated transcriptions of video/audio recordings of two student dyads, transcriptions of the teacher's recorded classroom observations, and observations of whole-class interactions taken from a video recording of the MBL. These transcriptions were supplemented by field notes of the teacher, photocopies of the students' classroom notes, copies of their computer-generated graphs, transcriptions of semi-structured interviews with students dyads, and transcriptions of the teacher's speech during lessons which followed the MBL activities (see Table 3.2).

Table 3.2

Data Sources Related to the Research Questions

Technique	Research question 1	Research question 2	Research question 3	Research question 4
Participant observation (journal and audiotapes)	X	X	X	X
Student interviews	X	X	X	X
Artefacts (POE notes and disk graph data)	X	X	X	X
Videotapes of main laboratory	X	X	X	
Audio/videotapes of two dyads	X	X	X	X

3.3.3 Setting

The MBL is an appropriate setting for research in physics education. The laboratory is central to scientific inquiry, subject to certain cautions. Novak (1988) associated the failure of laboratories to help most students gain key science concepts with:

> [teachers'] obsolete epistemology . . . The view of science presented was more consonant with . . . empiricist or positivist views than with more valid constructivist views. Experiments were shown to be ways to "prove" or "falsify" hypotheses rather than a method to construct new conceptual-theoretical meanings. (p. 405)

Based on a review of literature, Tobin (1990a) typified a learning laboratory as one in which the teacher chose tasks that perplexed students, and promoted inquiry, cooperative learning and social collaboration. MBL methods are potentially supportive of such constructivist inquiry. Students are able to access, display and analyse data quickly and repeatedly, allowing more time for reflective discussion. The graphical presentation of the screen display introduces a new entity to the group, providing interesting possibilities for altering the group dynamics of conversation. The MBL context may facilitate new and different patterns of student learning.

The research was conducted in a large government high school in Brisbane, where the researcher has used MBL activities in junior science and senior physics classes for 18 years. The school has an excellent reputation for academic, sporting and cultural achievements, and a high proportion of senior students proceed to tertiary studies. Twelve computers equipped with interfaces and supporting software (Appendix 2) are part of the normal equipment of the physics laboratory cum classroom in which the research was conducted. The room is relatively large and well equipped, with laboratory benches around the perimeter and desks and chairs centrally located in front of a raised demonstration bench and whiteboard. Students stand at the benches while they experiment (Figure 3.1). Two adjoining preparation rooms were utilised to provide quieter locations for two pairs of students to carry out their MBL activities under conditions that were conducive to audio recording, but which still maintained the essential aspects of the normal classroom. Appendix 3 shows a plan diagram of the locations of cameras and computers.

Figure 3.1. Students work at benches in the main laboratory while the teacher circulates from group to group.

3.3.4 Participants: Teacher and students

The researcher approached this study as a participant observer in his own classroom. He wore three hats: manager, teacher, and researcher. The first required that as teacher he ensure that his students complete obligatory coursework within a set time frame determined by the mandated work program of the school. The second situated him as an actor in a teaching/learning enterprise surrounded by other actors (students, monitors, laboratory equipment and other assemblages). His third role was that of a researcher seeking to document and interpret activities in the MBL. The teacher viewed himself as a facilitator of knowledge construction, "helping learners construct [their] ideas without violating constructivist learning principles" (Matthews, 1997, p. 13). This required that he circulate from group to group as described by Driver et al. (1994):

> Here, the critical feature is the nature of the dialogic process. The role of the [teacher] has two important components. The first is to introduce new ideas or cultural tools where necessary and to provide the support and guidance for students to make sense of these for themselves. The other is to listen and diagnose the ways in which the instructional activities are being interpreted to inform further action. Teaching from this perspective is thus also a learning process for the teacher (p. 11).

The teacher conducted his research with his Year 11 physics classes of 1999 and 2000. Each year he teaches one of the two Year 11 physics classes in the school. Classes average about 20 students studying their first year of specialist physics. These students have studied junior science including a six-week module on thermal physics in Year 9 and a nine-week module of physics in Year 10. They were familiar with sketching distance-time graphs and using formulae to solve simple problems involving distance and speed. The students had prior experience with MBL techniques. Physics students constitute some of the top academic classes in the school. Up to one quarter of the students are females, whose academic results are in the upper two-thirds of the class. Records from previous years suggest that of every 20 students about 16 will pursue science-related tertiary studies, and of these about 8 will include at least one semester of physics. Physics students are typically well behaved, cooperative, and committed to their science studies.

3.3.5 A constructivist approach to the physics laboratory

On the basis that the teacher/researcher in this study is committed to a teaching and learning approach consistent with constructivist principles, it is fitting to distil from the discussion to date some guidelines used in his laboratory lessons. The following guidelines are not topic specific, nor intended as a teaching methodology. Some of the components have drawn on the earlier literature reviews of MBL activities conducted within a constructivist framework.

3.3.5.1 Preparatory activities

- Discuss with students what constructivist teaching and learning is all about, and how the ideas may be novel to them.
- Find out what the students understand about each topic beforehand. This may be their understanding as a cohort. Many individual understandings may only become clear to the teacher during the course of their laboratory activities.
- Equip students with the techniques and tools for the laboratory activities. Students should be given prior experience at using the MBL equipment (Clark & Jackson, 1998; Matthews, 1997). Introduce the meanings of new terms relating to the topic or the meanings of old words used in new scientific ways (see Appendix 4).

3.3.5.2 Students' laboratory activities

- Students work cooperatively, sharing their ideas within and between groups, by talking and writing science.
- Address problems that relate to real-world events. This has the potential to help students associate their prior (non-scientific) concepts with concepts in the laboratory.
- Plan and execute open inquiries that provide opportunities for predicting and observing, and to produce conflicts and confirmations of ideas.
- Allow time for repeated investigations (hermeneutical cycles), for deep mental engagement, and to resolve conflicts.

3.3.5.3 Teacher activities

- For the initial activities, present opportunities for students to focus on basic concepts. This implies some structure is imposed on the student-centred activities (see Driver et al., 1994). Some form of worksheet (McLellan, 1994; Rogers & Wild, 1994; Solomon et al., 1991; Tao & Gunstone, 1997a) provides this structure and allows the teacher to circulate amongst the students.
- Listen to students and act as a facilitator by the use of appropriate questions.

3.3.6 MBL activities

Throughout the research period class activities followed the same pattern of content, procedures and time allocation normally planned for kinematics and thermal physics modules. Such an authentic setting added significantly to the value of the study.

The MBL experiments made use of an electronic computer interface (see Figure 3.2 and Appendix 2) designed and constructed within the school by the researcher, and used in scores of neighbouring schools over the past 12 years. It has proved easy to use, reliable, and features versatile data logging and graphing capabilities with sophisticated smoothing routines.

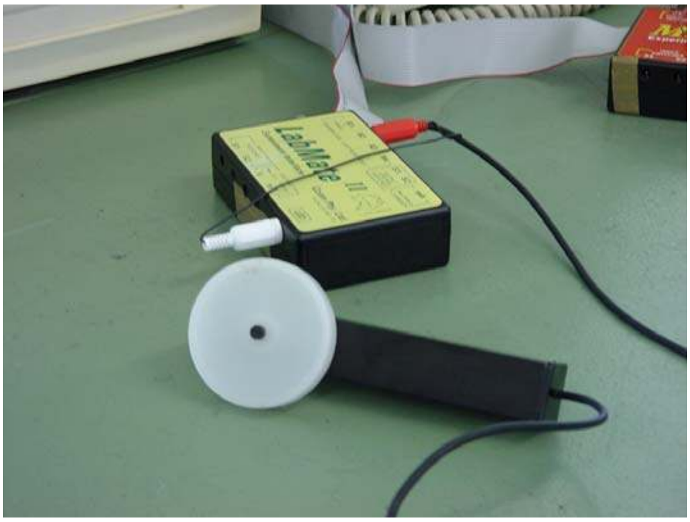


Figure 3.2. The interface and wheel sensor used for kinematics experiments.

The classroom laboratory has accumulated twelve IBM compatible computers discarded from other school departments. Each is fitted with a colour monitor, hard disk drive and interface. The computers are stationed permanently around the periphery of the classroom/laboratory and experiments are conducted on six large benches adjacent to the computers. For the purposes of obtaining clear audio recordings of students' dialogue two of the computers were transferred to smaller adjacent rooms. Though the doors between rooms were normally shut, students and teacher moved freely between rooms in order to share equipment and ideas.

DOS software authored by the researcher is installed on the hard drives and controlled by the keyboards. To log data capture, students enter the data range for each sensor being used and the time duration of the experiment. During data collection the screen displays a real-time graph. Each graph can be saved, cleared and recalled, and multiple graphs can be overlaid on the one set of axes. A hand held wheel sensor measures displacement in motion experiments, and two probes sense temperature simultaneously for heat experiments. Data are displayed as displacement-time graphs, temperature-time graphs, or as numerical data tables. Once displacement data have been logged and displayed as a displacement graph, velocity and acceleration graphs can be generated and displayed at the stroke of a key. The MBL gives each dyad the capacity to gather data quickly and repeatedly at the bench top alongside the computer display. Other proprietary interfaces produce essentially the same graphs, with varying degrees of sophistication. This means that the procedures used during the research should be reproducible in other MBLs, noting the caveat that each commercial hardware and software product has a different intrinsic level of user friendliness.

The study of kinematics and thermal physics are major themes that are introduced to the Year 11 students in semesters 1 and 2 respectively. During Part 1 of the main study one class conducted thermal physics experiments, and in Part 2 a different class conducted kinematics experiments. Both topics have been the subject of numerous research reports during the history of MBLs and a number of these were discussed in the literature review.

The first reason for this replication feature is that the physics of the two areas differs considerably. Much is known about the conceptual and graphing misconceptions students display in separate studies of motion and heat (Barclay, 1986; Lewis & Linn, 1994; Linn et al., 1987; McDermott, 1991; Mokros & Tinker, 1987; Nachmias, Stavy, & Avrams, 1990; Thomaz, Malaquias, Valente, & Antunes, 1995; Weller, 1995; White & Gunstone, 1992; Wiser & Kipman, 1988). By including both in the current research the teacher/researcher intended to obtain a rich body of research data that would enable him to compare and contrast students' learning from MBLs in two different domains. Findings from the present interpretive study are likely to add to understanding from earlier studies, the majority of which were essentially quantitative in nature and based on pre- and post-treatment analyses.

Additional support for this two-domain study is drawn from the report by Driver et al. (1994) of studies of pupils' understandings of light rays and atmospheric pressure. They wrote:

> The examples presented here draw attention to the fundamental (but frequently overlooked) point that different domains of science involve different *kinds* of learning [italics theirs]. . . We suggest that these differences in student response can, in part, be accounted for by considering the ontological and epistemological demands of learning in the separate science domains in question. (p. 11)

Finally, selecting two domains of physics enabled the researcher to explore the generality of claims about MBLs in students' learning: "The generalizability of any theory can only be established through verificational studies" (Hutchinson, 1990). A goal of the present study is to identify features common to both domains and to make appropriate applications to teaching. The objectives of the present research, as stated in section 1.2, are not intrinsically oriented to a specific topic in physics. They focus, not on the substantive physics, but on the MBL nature of the experience.

In designing MBL activities, attention was given to a number of guidelines. Firstly, MBL materials must be "ready to hand" (Roth et al., 1996) (familiar to and readily accessible by students), considering the finite time available for each curriculum topic (Clark & Jackson, 1998). For this reason students were allowed part of a lesson to familiarise themselves with the new apparatus and software prior to formal experiments. Secondly, instructional material should amplify opportunities for student-student-computer interactions, while at the same time provide sequential inquiry steps (Maor & Taylor, 1995). Heeding these requirements, the student materials, written in a predict-observe-explain format, were refined and trialled in the year prior to data collection. Thirdly, students need assistance with activities and manipulation of the software, as they are prone to construct unintended meanings (Roth et al., 1996). Teacher guidance took the form of asking students to elaborate on their responses, posing leading questions to focus students on contradictions, and encouraging inter and intra-group interactions (Novodvorsky, 1997). Experience shows that despite a teacher's commitment to a constructivist epistemology, classroom intervention can easily drift to a transmissionist approach (Tobin et al., 1997). This required that the teacher be aware continuously of his own role as he engaged students in conversation during the lessons.

3.4 METHODS

By what means can we come to know what and how students are learning? The physicist Penrose (1989) reflected on the complex nature of this question. "The little knowledge that I have myself acquired about how the human brain works – and, indeed, any other living thing – leaves me almost dumbfounded with awe and admiration" (p. 539). A method which approaches this question from a simplified direction is that described by Lemke (1990).

> Undoubtedly, there are physiological relations among processes in the brain and the rest of the body as it interacts with its physical environment that correspond to what we call "using a conceptual system." But the fact is we know next to nothing about the rules of that correspondence . . . On the other hand, there are a large number of easily observable phenomena for which we do already know how they correspond to meanings that are important to us in science or other fields: speaking, writing, drawing, calculating, experimenting, and so on. Of these, we know the most about processes of action that make meanings of using language. (p. 99)

Lemke's view is that students' concepts do not exist in the abstract, but are constructed by their use of speech, supplemented by writing, drawing, experimenting and so on. Learning in science is a very much a discursive activity. In the classroom laboratory discourse is taken as "the conduct of immediate social interaction by verbal and nonverbal means . . . the dialect of science in face-to-face conversation with others" (Erickson, 1998, p. 1157). Verbal discourse is closely linked to bodily and facial gestures, note taking, eye-contacts, prior and concurrent physical activities, monitor display symbols and any other actions that give an indication of how students are thinking. Styles of conversation are affected by the classroom culture, the subject at hand, and the instructional activities of the moment.

Bakhtin (1986) developed a theory of language centred on utterances as opposed to grammatical sentences. A word, phrase or sentence once uttered takes on a social meaning or makes sense. Drawing on the work of Bakhtin and other theorists (for example, Gumperz, 1992; Lemke, 1990), contemporary educational research in science has developed a tradition of using sociolinguistic methodologies for students using MBLs (Crawford & Kelly, 1997; Kelly et al., 1998; Nakhleh & Krajcik, 1993; Roth, 1994; Settlage, 1995), experiment simulations (McLellan, 1994; Roberts et al., 1994; Roth et al., 1996), and presenting science speeches (Bleicher, 1994).

As discussed previously in section 3.2.3, research methods drawn from the field of discourse analysis are extremely informative for questions about how knowledge is socially constructed and communicated in the laboratory. Language serves as a mediator for students' thinking and learning. An analysis of their discourse has the potential to reveal what students learn from their laboratory work, how they construct and reconstruct meanings, and the patterns of interaction between each of the players in the laboratory (including computer representations of data). Confirmation of the interpretation of thinking processes may be derived from an analysis of textual materials, such as student notes and diagrams that are composed in association with their dialogue.

3.4.1 Classroom strategy

Prior to both parts of the present study all students in the class were invited by letter to participate and to give their informed consent. As the students were assured of anonymity to all but the researcher and his supervisors, and no aspect of the research would affect their assessment, all agreed. Prior to each part the students were observed working in self-selected dyads in the laboratory. Consideration was given to choosing pairs of students who were articulate and cooperative, for videorecording during the actual research. For each of Part 1 and Part 2, one pair remained unchanged for four consecutive lessons so as to obtain a continuous record of their activities with the topic. For the second videotaped dyad, two different pairs of students were used for each part. This meant that, within the limitations of time (four laboratory lessons for each of Part 1 and Part 2) and space (two recording rooms), a more diverse range of students could be studied. Thus the dyads videotaped in the second room included a pair of females, a mixed pair, and two pairs of male students.

Other studies that have involved pairs of students working with computers have selected students by different criteria. For example, Tao and Gunstone (1997b) mixed high and low achievers to maximise peer conflict. Lidstone and Lucas (1998) recommended pairing students by study skills and personality factors. Their study involved post-graduate adults drawn from diverse backgrounds for one week of cooperative study. However, for the present study there was no compelling reason either from the literature or the teacher's personal experience to pair students other than in friendship groups. The students were accustomed to such arrangements.

Prior to each part the students were given time to familiarise themselves with the sensors and software. This was the "experiencing" category described by Thomas and Hooper (1991) that provides motivation, structure and awareness. It allowed students to settle into their dyad relationships and learn how to use the equipment. Part 1 (thermal physics) and Part 2 (kinematics) each began with the teacher's introduction to the meanings of new terms and techniques for handling new equipment (for example, the new term thermal equilibrium, and introducing the calorimeter as an instrument). Subsequently, students conducted their experiments, the "integrating" category of Thomas and Hooper, by which knowledge elements are brought together into collective applications. Classroom research began at this juncture. Some time at the start of each 70-minute lesson was required for administrative purposes.

To promote joint on-task engagement, worksheets were written, based on POE tasks (see Appendix 5), consistent with the constructivist approach espoused (Liew & Treagust, 1998). The worksheets required written reports of students' experiments using a flexible format. In preparing the POE tasks, the researcher was mindful of the experience of Maor and Taylor (1995) by which their worksheet booklet unintentionally supported individualised rather than cooperative learning, and became prescriptive of instructional steps. The tasks gave student pairs latitude in the design of their experiments (admittedly within the limits of the available equipment) and expressly encouraged communication between groups. The researcher trialled worksheets for the motion module during the pilot study. A series of seven POE tasks involving motion required students to plan, execute and record physics activities.

3.4.2 Data sources

The study used as data sources video and audio recordings of group activities while students experimented, teacher audiotapes, teacher journal, student POE worksheets, semi-structured interviews of students who were videotaped, and also a number of other dyads, as well as written examination answers relevant to the physics modules studied. The teacher-researcher and a researcher-assistant installed, maintained and dismantled the equipment and collected the data. Two video cameras were mounted (see the plan in Appendix 3) to record the activities of two dyads, with microphones to record their conversations. The computer monitors were linked to the video recorders to superimpose on the top right corner of the videotape the monitor display as seen by the students (Figure 3.3).

Figure 3.3. Video monitor showing the students and teacher viewing the computer display, a small copy of which is superimposed in the top right corner.

In addition to copying the dyads' POE notes, images of graphs generated and saved by the students during the MBL activities were copied from the computer hard drives. All these data enabled the researcher to interrelate experiment tasks, conversations, actions, the monitor display and POE notations in an event-by-event time sequence. During transcription of the videotapes, the researcher was able to cross-check each student's words and actions with what he or she was viewing or touching on the monitor, writing in POE notes, or manipulating on the experiment bench, at the time. POE notes written during a laboratory lesson could be distinguished from those written for homework that evening. The transcriptions were numbered by turns of speech. Annotations of students' gestures, graphs generated during the MBL activities, and contemporaneous POE sketches were added. Thus the transcriptions provided a detailed and reliable record of dialogue and actions, with very few words unable to be understood.

In class the teacher-researcher was a participant-observer. He recorded and transcribed his speech and observations during each lesson and after each lesson made notes of key events and issues that required following up in subsequent lessons or interviews with students. Audiotapes were made of the lessons immediately before and after the research period. Recordings of teacher audiotapes are prefixed 'AT' followed by the six-digit date (day-month-year).

During and after the data collection period the teacher conducted a number of semi-structured interviews with each of the videotaped dyads, as well as with three or four other dyads in each class. The timing and frequency of these interviews were somewhat curtailed by students' availability. The interviews made frequent reference to students' understanding of specific POE tasks, the nature of dialogue between dyads, and their positive and negative impressions of the MBL activities. These interviews, and audio recordings of the teacher's whole-class lessons before and after the MBL lessons, were transcribed. Student interviews are prefixed 'AS,' followed by the number of the interview for the particular day, and the six-digit date.

3.4.3 Data analysis techniques

Figure 3.4 shows the relationship between the data sources and the analytical processes. The boxes on the upper right hand side of Figure 3.4 show how the four research questions were linked to the analysis.

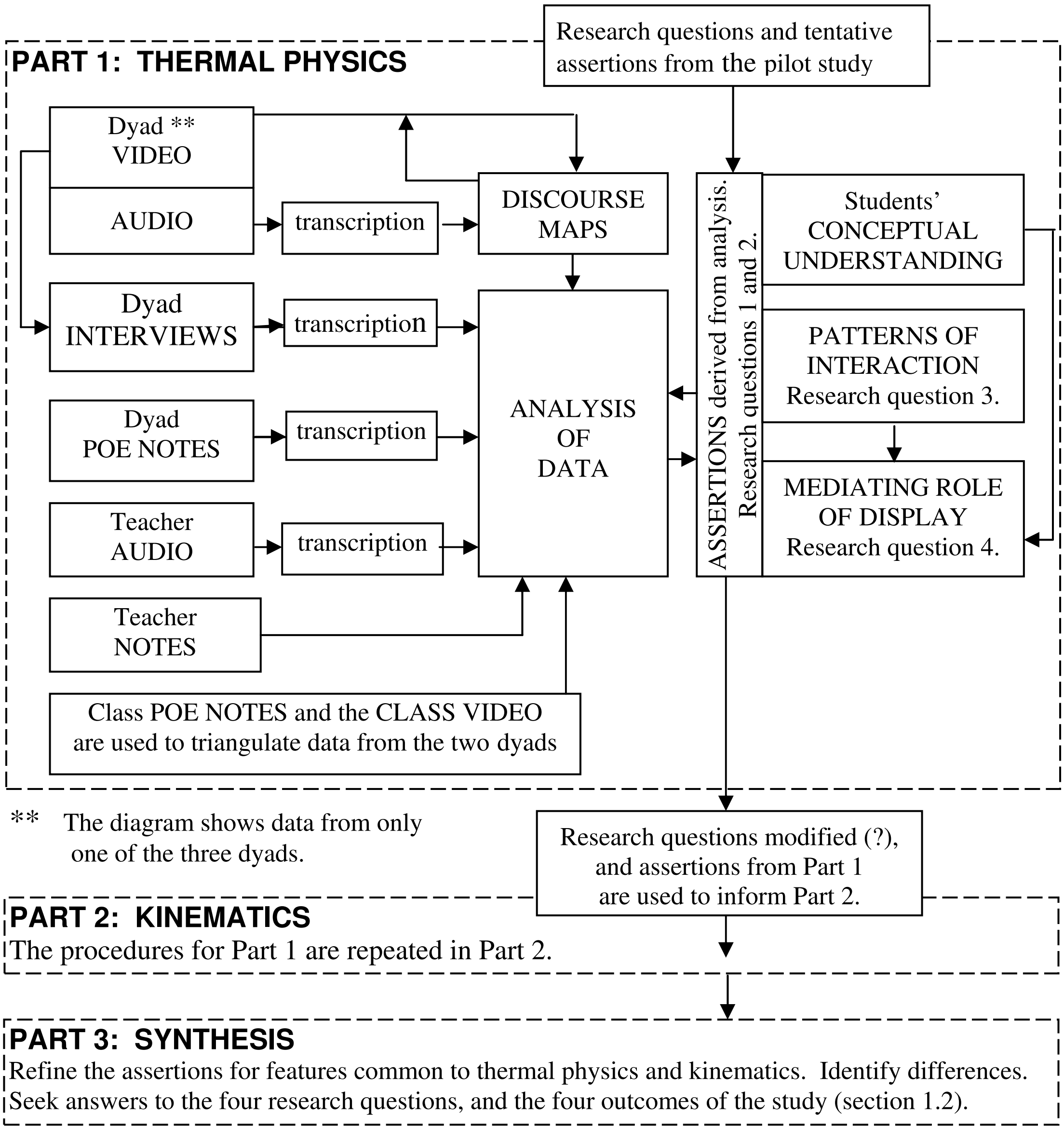


Figure 3.4. Data sources and their relationships to the data analyses for thermal physics and kinematics.

Some tentative working assertions from the pilot study guided the analysis of the annotated transcripts in Part 1 (thermal physics) (see chapter 4). A variety of techniques based on discourse analysis was used to learn about students' patterns of interaction, their construction of scientific concepts, and how the computer display mediated their understanding of thermal physics. The analysis followed a recursive pattern, searching for both typical and atypical examples of student interactions. Even though the analysis was qualitative, attention was given to the frequency of occurrence of these phenomena, to distinguish between typical and atypical occurrences. The analysis followed certain themes, and dimensions within those themes, and arrived at a number of assertions in answer to the research questions. Students' POE notes written during the lessons, the teacher's post lesson notes, and the semi-structured interviews with each dyad, were searched for confirming and disconfirming data. The interviews also provided an opportunity to clarify aspects of students' interactions with the MBL equipment, and their joint construction of understanding of the physics involved. Finally, the video recordings from the camera located in the main laboratory, and the POE notes written by all students during the MBL activities were examined to ascertain the extent to which there were similarities and differences between all other students and the dyads studied.

The findings and assertions from Part 1 (chapter 4, thermal physics) guided the analysis of Part 2 (chapter 5, kinematics). While it was anticipated that the initial research questions would have to be revised or added to during the course of the study (Erickson, 1998), this proved not to be the case.

A synthesis of Parts 1 and 2 appears in chapter 6. This synthesis addresses the four research questions and the four outcomes of the study stated in the research objectives (section 1.2).

3.5 PILOT STUDY

A pilot study having the same content as proposed for Part 2 (kinematics) was conducted with a Year 11 class in March of 1999. The physics topic of the three laboratory lessons was an introductory module on displacement, velocity and acceleration. One dyad was video and audiorecorded for detailed analysis. The teacher's conversations and observations were recorded on audiotape and the main classroom/laboratory was videotaped. The dyad was interviewed one week following the three 70-minute experiment sessions.

A number of lessons were learned from the pilot study. The decision to locate the dyad for special study in an adjoining room in order to obtain more distinct voice recordings was vindicated. Though separated from the main classroom, these students had free and easy access to the other students in the class and to the teacher, and reported that they did not feel isolated from the regular lesson. In order to obtain audible tapes for transcription students who speak with reasonable clarity and volume should be chosen. An ample supply of tapes should be on hand, as well as making sure that all tapes are activated at the start of each lesson. Careful planning is needed to ensure none of the selected dyads is involved in other school activities during the research period, and all can make themselves available for interviews when needed. Following the pilot study, the first POE task (Appendix 6) was broken down into four separate tasks to help students scaffold their understanding better. While students readily moved the hand-held wheel to reproduce a graphical representation of constant velocity, their efforts at representing constant accelerated motion by freehand movement were less successful. The POE task to model acceleration was re-written to suggest that students use a falling weight to collect acceleration data.

The pilot study showed the value of copying the dyads' motion data stored in the computer hard drives, for reference when transcribing their dialogue. Hence for the main study all groups were asked to save their data. This required teaching each group how to name data files systematically for later identification. Also, the computer time-of-day settings and clocks in all rooms had to be synchronised before each session to facilitate coordinating events that appeared later in transcriptions of the video and audio recordings. Subsequently, during Parts 1 and 2 comprehensive printed samples of all students' graphs were available for analysis.

The principal benefit from the pilot study was that it determined an audiotape transcription format suitable for discourse analysis. A sample page of transcription appears in Appendix 7 (see Appendix 9 for the transcription symbols). The features include student pseudonyms, the current POE task being attempted, line numbers of turns of speech, periodic time stamps, student dialogue, non-verbal cues, and small reproductions of the screen display and/or students' POE sketches being referred to at the time of their speech.

The researcher learned from reviewing the videotapes that he tended to intervene overly much in student conversations. This was in part due to his concern that the first POE task was lacking in the degree of direction that it gave his students. Additionally, the researcher's personal observations recorded during the lessons needed to be more descriptive of the details of students' activities. This required that he give more thought to the substance of what he intended to observe before each lesson commenced.

The research design, selection of participants, experimental tasks, data sources and data analysis techniques as adopted in the pilot study confirmed the potential of the study to provide answers to the research questions. For example, a tentative description of the patterns of interaction in the MBL was developed (Appendix 8) from viewing the videotapes and analysing students' dialogue. The results of the data analysis provided fruitful insights into the roles of the display in mediating students' understanding of motion, the evolution of students' use of scientific terms over time, their joint engagement on tasks and construction of meaning, and the wide variety of techniques to which students resorted in order to interpret graphs. The researcher's experiences with analysing and triangulating the various data sources reassured him that each source contributed meaningfully to the analysis. A paper jointly authored by the researcher and his two academic supervisors, based on the pilot study, was presented at the annual conference of the Australian Association for Research in Education (Russell, Lucas, & McRobbie, 1999).

This chapter has described the methodological approach and design of the present study. In broad terms it has drawn a picture of the classroom setting, the students' and teacher's backgrounds, and preparations for MBL experiments put to test with a pilot study.

The formal research was conducted in two parts, Part 1: Learning About Thermal Physics in an MBL and Part 2: Learning About Kinematics in an MBL, and is reported in chapters 4 and 5. Each chapter describes its own specific features: the class of students, the dyads selected for close study, the nature of the physics involved, and data collection. The chapters analyse data from a number of perspectives, each leading to a discussion and one or more assertions. Both chapters conclude with a summary of assertions, which encapsulates the main features of student learning in each of the areas of physics. The data analysis in Part 2 differs slightly from the approach in Part 1, due to the differences in student groups and the nature of the physics involved. Chapter 6, Discussion of learning in MBLs, compares and contrasts the ways students learn physics in these two domains.

CHAPTER 4: LEARNING ABOUT THERMAL PHYSICS IN AN MBL

The study of heat and temperature is a very productive field for the present research. The range and depth of physical principles that students can investigate is very broad and the principles have extensive applications in daily experiences. Temperature sensors are inexpensive, robust, and are as easily used in the laboratory as mercury-in-glass thermometers. Most of the difficulties that students experience with thermometry and heat transfer are associated with experimental techniques (for example using a calorimeter) rather than with MBL hardware and software. A distinctive feature of heat experiments is that temperature changes and heat transfer are (mostly) invisible and usually take place slowly. This contrasts with motion studies in which objects are seen to move, and quickly at that. Students bring to class a wealth of prior knowledge and mental models of heat and temperature (Harrison, Grayson, & Treagust, 1999; Thomaz et al., 1995; Wiser, 1995).

Alternative or underdeveloped conceptions held by some students are: (a) Heat is a substance residing in objects, which can pass from one to another; (b) heat energy and temperature are synonymous; (c) the meaning of thermal equilibrium; (d) adding or losing heat during a phase transition leaves temperature unchanged; (e) the notion of the amount of heat energy transferred; and, (f) specific heat phenomena (Thomaz et al., 1995; Wiser & Kipman, 1988). The structured POE tasks developed for the thermal physics experiments expose students to all of these concepts.

Heeding advice from the literature (Clark & Jackson, 1998; Driver et al., 1994; Thomas & Hooper, 1991) the teacher conducted an introductory lesson prior to laboratory activities. He distributed and discussed briefly an introductory handout of concise meanings of new terms (Appendix 4). The students were asked to use this as a resource document for the laboratory lessons. The teacher demonstrated how to use the temperature sensors, MBL temperature software, and calorimeters. Working in self-selected pairs, the students then spent fifteen minutes familiarising themselves with computer software and temperature sensors. The students were already familiar with the generic keyboard commands and appearance of screen graphs due to their previous experience with kinematics software. The teacher also reviewed the POE procedures which the students had used earlier in the year with the pilot study of motion (section 3.5).

During four 70-minute MBL lessons the students addressed thirteen POE tasks (Appendix 5) (Linn & Songer, 1991b; McLellan, 1994; White & Gunstone, 1992), which they approached at their own pace, and homework questions that drew on and extended each day's activities. The POE tasks were structured to introduce a sequence of concepts: the time taken for a sensor to reach thermal equilibrium with a body; calculation of the time constant for a sensor measuring temperature under varying conditions; the production of heat energy by friction; thermal conductivity; cooling curves including a phase transition; the difference between heat and temperature; and, identifying the variables which affect the heat content of a body. In the lessons following the first MBL session, the teacher spent the first ten to fifteen minutes asking students to expand on their findings and explanations of the previous day's tasks. During the post-MBL lesson he led a class discussion of the students' answers to the tasks and homework problems. For much of this review students responded to overhead transparencies of graphs created by students during their earlier experiments, and which the teacher selected by accessing their stored data.

The physics class participating in Part 1 included thirteen boys and two girls who worked as six dyads and one triad at seven computers. (The term dyad will be used loosely in future to include the triad). Three dyads, comprising articulate students (but otherwise not atypical of others in the class), were selected to be videotaped and audiotaped as follows (pseudonyms being used): Mike and Ivan for all four lessons, Mark and Shaun for lesson 1, and John and David for lessons 2 to 4. The class had just completed its first semester of physics and all students had passing grades with eight achieving at "A" standard where "C" is a passing grade. Based on class assessment for the first semester, Mike and Ivan ranked 3rd and 10th respectively, Mark and Shaun ranked 14th and 13th, and John and David ranked 5th and 8th.

The primary sources of data for analysis were the student protocols in the form of transcriptions taken from the audio recordings of dyads, annotated with descriptions of students' gestures and expressions, features of the concurrent screen display, and experimental procedures and notes written during their conversations. These transcriptions and the dyads' POE notes were read many times and the decision was made to structure the analysis around two themes which relate closely to the research questions: patterns of interaction in the MBL, and students' understandings mediated by the display. This chapter will now pursue each theme in turn, using analytical methods that develop a number of dimensions within the themes. Appendix 9 gives a description of the coding system and conventions used in the transcriptions of student dialogue, and the coding for transcriptions of interviews.

Some passages of dialogue will be analysed from different perspectives, and hence used more than once as vignettes. For example, lines 285 to 335 of the dialogue between Mike and Ivan (Dyad A) appear in section 4.4.2 to illustrate how students use a variety of conceptual models in graph interpretation. The same passage appears in section 4.4.3 as an example of teacher interactions with students. In chapter 4 eight passages of dialogue are analysed more than once.

4.1 PATTERNS OF INTERACTION IN A THERMAL PHYSICS MBL

4.1.1 Identifying and illustrating network relationships

Firstly an attempt was made to identify the interactive elements in the MBL. Careful viewing of the video recordings from all cameras identified these as: students, teacher, computer display, experimental apparatus (including the interface and sensors), and worksheet/POE notes. The non-distinguishing of social and non-social elements as active participants shaped their involvement with each other in a network, was suggested by actor-network theory (ANT) (Bigum, 1998b; Lee & Brown, 1994), which has been used to describe sociotechnical systems in classroom activities (Roth et al., 1996).

From an ANT perspective the patterns of interaction and the strengths of associations between these actors assume prime importance (Bigum, 1998b). The video and audio recordings showed that these relationships changed from moment to moment as students worked through their tasks. Prior experience from the pilot study with kinematics (Russell et al., 1999), suggested that the dialogue be read from the perspective that students progressed through five stages: (a) understanding the problem and <u>predicting</u>, (b) <u>setting up</u> and commencing the experiment, (c) collecting data and <u>observing</u>, (d) <u>analysing</u>, and (e) <u>explaining</u> the results. Future references to the five stages will be made using the key words that are underlined. A reading and re-reading of the transcripts of student dialogue identified these stages, and confirmed that the five stages were appropriate and sufficient for analysis of the dialogue.

When items of laboratory equipment to be used for the task were novel, the first two stages (a) and (b) often overlapped. The students inspected the apparatus as an aid to understanding the task and formulating predictions, while at the same time they set up the experiment. When experiments were extended over time, as most were, the next three stages (c) to (e) were also closely linked. Students often intertwined observations, analysis and explanations. As graphs grew slowly over many minutes students formulated and re-formulated their running commentaries. The five stages and the links between them are tabulated in the first two columns of Figure 4.1. Notwithstanding this overlapping, the stages remained identifiable in terms of the students' conversations and actions.

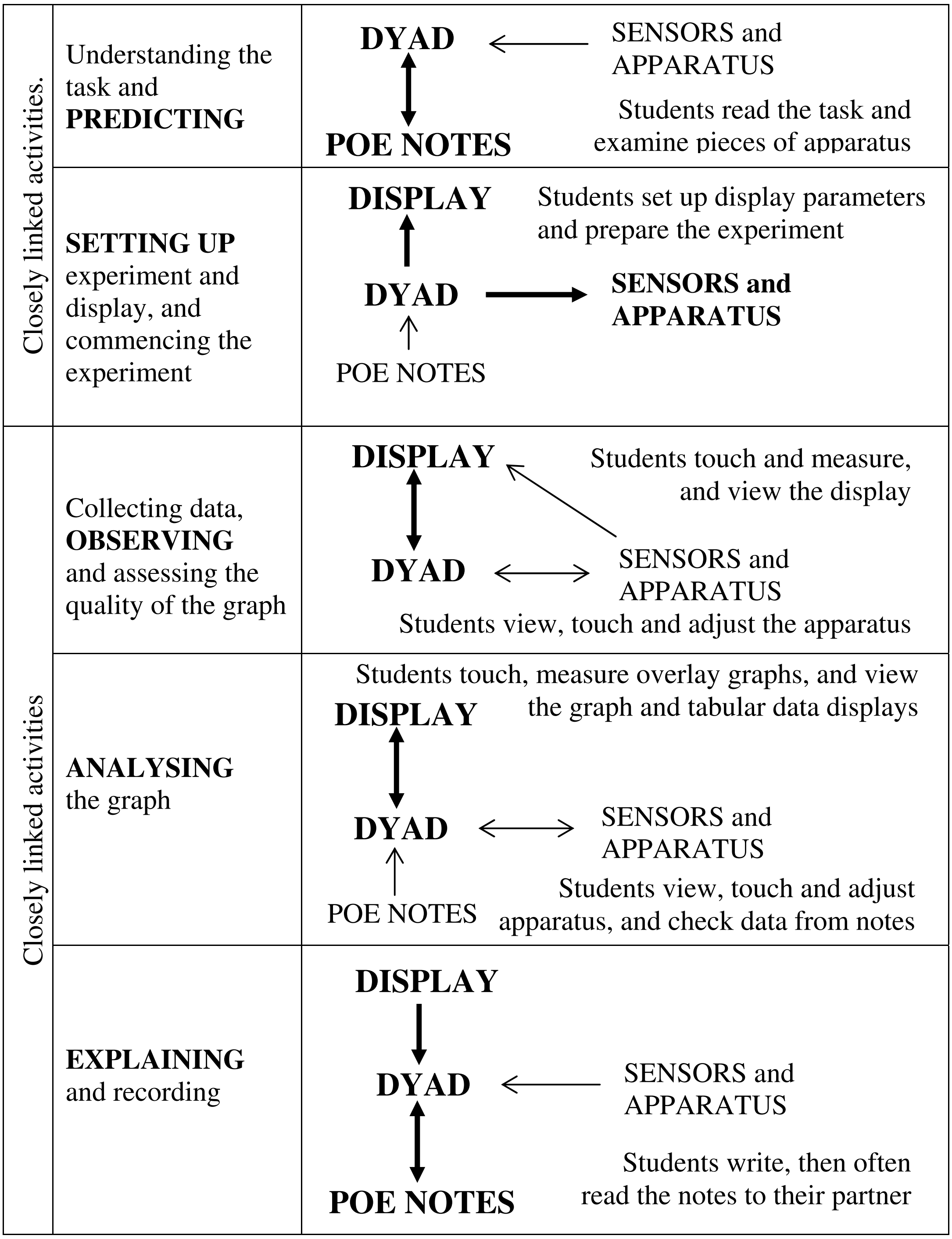


Figure 4.1. Networks of interactions during thermal physics tasks, showing five stages through which students progressed in handling tasks.

The second column describes the five stages through which students progressed in handling tasks. The third column illustrates the network relationships that commonly occurred between the actors at each stage. The boldness of the type indicates the significance of the actor. The thickness of the arrows indicates a judgment made as to the frequency of the flow of information from an actor, or attention given to an actor. Arrows indicate speech, reading, a gesture, viewing, writing, feeling, setting up, or sending as an analog signal. The term dyad is used to simplify the diagram. However, within the dyad conversation and non-verbal messages passed continually between the students. Student-teacher and inter-dyad communications are omitted from this diagram because they were interspersed irregularly throughout the five stages. Nevertheless, they certainly were not insignificant. During the four lessons the teacher spoke at some length with the videotaped dyads on 56 occasions. The selected dyads in the two smaller rooms communicated with each other on nine occasions, and ten times they approached or were approached by dyads from the main laboratory about matters relating to the POE tasks (as opposed to merely borrowing equipment). A final omission from Figure 4.1 is the recourse students made to prior concepts and experimental experience, which occurred to varying degrees during all five stages.

The following sub-sections use vignettes to introduce the laboratory atmosphere and illustrate the directions of dialogue and actions that identify with the arrows in Figure 4.1, and provide evidence to support this representation.

4.1.1.1 Predicting and Setting up.

As a prelude to each experiment, the students read their task, discuss it, set up the apparatus and write their predictions. The arrow points from POE NOTES to DYAD as they read, and reverses as they write predictions. The arrow from SENSORS and APPARATUS to DYAD indicates the students are literally getting a feel of the equipment, to flesh out as it were the wording of the POE task. Some of the speech passages that follow are illustrative of arrows or links in the directed network. The reader can match the relationships revealed in the lines of speech with some (but not all, for the examples chosen are not comprehensive) of the corresponding links in the diagrams. Other passages reveal exceptions to the network, such as a missing prediction stage, or an uncommon link not shown in Figure 4.1.

A careful reading of POE notes from students in the main laboratory suggests that all but one or two students customarily completed the prediction stages. However, this is problematical since they were not videorecorded, and they may have completed some prediction sections after the experiment. Mike and Ivan bypassed the prediction stage for five of the ten tasks. Mike, very confident, tended to lead Ivan into experiments before discussing the problem, which resulted in their having to halt and re-start experiments on four occasions. Consider their approach to the first task:

> Task 1.1: Does a thermometer or temperature sensor, initially at ambient temperature, give an <u>instant</u> reading when placed, say, in hot water?

Their conversation (by line numbers of turns-of-speech) proceeded:

3	Ivan	Which one will we do first?
4	Mike	We need to make a graph of heat . . . (Ivan starts to write, Mike sets up the screen graph details.)
(The students immerse the sensor in hot water and watch the graph grow)		
18	Mike	It's probably only going to go up to 75 (both touching the screen).
19	Ivan	It'll go to 60 70 80 up to 100 . . . that'd be 75 (touching the screen). It's started to decrease in temperature now . . . (There is a long pause as both look at screen, then turn to their notes.) What's this with the prediction? Shouldn't we do that first? . . .
20	Mike	We must predict it's not going to go instantly to the maximum. (Both write their predictions after the event.)

For the same task Mark and Shaun read the problem, but started the experiment before arriving at a consensus as to the purpose of the experiment and making their predictions. They had started the graph and were about to place the temperature sensor in hot water.

18	Mark	Now stick it in. Stick both in. (Shaun puts one sensor in beaker of hot water for 7 seconds. Mark picks up the second sensor and puts it in for 5 seconds. Both look at screen.) So it does. ["So it does" refers to the question "Does the sensor give an instant reading?"] (Mark then removes Sensor 2, and Shaun removes Sensor 1.)
19	Shaun	Yup.
20	Mark	Press F1 to stop? [i.e., the graph]
21	Shaun	Yup. So we write "Yes." (Shaun starts to write at the top of his notes then hesitates.) Hang on hang on (looking closer at the task question).
22	Mark	(Looking across to Shaun.) We're supposed to write that here – "Predicts" [i.e., to write "Yes" after the Prediction heading in his POE worksheet].
23	Shaun	No but that has to (??). (Shaun shakes his head, indicating the way they went about the task was wrong. He leans close to Mark and points with his pen to the question and directions in the worksheet.) "Does a thermometer . . . INSTANT reading when place in hot water." So it's NO, it doesn't give an instant reading of temperature of 80 degrees or whatever that is (touching beaker of hot water).
24	Mark	Yeah.

On carefully re-reading the question Mark and Shaun amended their prediction. As the videorecorded dyads became familiar with heat experiments their approach to the tasks became more disciplined. Typically at the start of each task one student read the task audibly, and both generally arrived at a prediction by consensus, although this was not always the case. For example, Shaun and Mark disagreed in their prediction for Task 1.1.

256	Shaun	(Reading aloud from Task 1.3 notes.) "If the sensor touches a hot object, such as one of the solid metal cylinders heated in hot water, how quickly will it measure the final temperature?"
272	Shaun	(He reads from his prediction note.) "The graph will rise quickly like Task 1.1."
273	Mark	I don't really know.
274	Shaun	Yes I think it will.
275	Mark	I mean. . .
276	Shaun	It'll probably get pretty hot.
277	Mark	I think that it will rise really quickly for a short period of time then it'll . . ah . . slack off . . . (Mark writes his prediction. Teacher enters room.)
284	Shaun	(He speaks to the teacher) We don't have to have the same predictions do we?
285	Teacher	Well no.
286	Mark	No because nobody has the same ideas and peer conflict and stuff like that.
287	Teacher	You might want to discuss it. You mightn't agree . . . on the other hand . . .
288	Shaun	Well we've both had different predictions, and one's been right and one's been wrong (Teacher: = Yes) then we've both been wrong.

Lines 256, 272 and 277 also illustrate the two-way relationship (of reading and writing) between the students and their POE notes during the prediction stage.

Students interchanged ideas and principles, using appropriate scientific terms, recalled previous results for comparison, and then predicted the graph shape. Students sometimes linked or overlapped the prediction and setting up stages. During set up they felt and examined the apparatus while at the same time conceptualised the task and arrived at their predictions. The following excerpt shows how students combined the prediction and setting up stages. In lines 130 through 147 both focused their attention on the test tube which Shaun had picked up, to help them understand the problem and reason on a prediction.

130	Shaun	(He reads slowly from Task 1.2.) "The temperature sensor is first placed inside a narrow test tube" – there's a narrow test tube (picking it up) – "and placed in hot water. How will this affect its operation?" Is that placing the test tube in hot water?
131	Mark	Yep that's placing the test tube in hot water.
132	Shaun	So it's the air inside this tube.
133	Mark	Yeah.
134	Shaun	Alright.

135	Mark	Because the test tube is hot and the air
136	Shaun	and there's air inside the test tube as well.
137	Mark	As long as the water temperature's hot . . (= hot yes).
138	Shaun	(= Hot yeah.)
139	Mark	Cause you must add the hot water, and then this water, (??) a different result.
142	Shaun	(Both read p. 4 top box.) "Can we mention thermal contact in the discussion?"
143	Mark	Thermal contact. NO. . . No we can't.
144	Shaun	Why not?
145	Mark	Thermal contact's physical contact.
146	Shaun	Yeah, but the water's touching the glass, the glass is touching air, the air's touching the sensor.
147	Mark	Yeah but the sensor's not touching the water (Shaun: No) so it's not thermal contact.
152	Shaun	(He reads the task.) "Estimate the time constant under these conditions." Oh I'd say it would (???). Alright . . are you using boiling hot water?
153	Mark	No we'll use the water at the temperature (as he gestures to the sink, intending to use hot tap water).
154	Shaun	Alright, how do you predict what will happen? . . . I reckon that the temperature will rise really slowly – but not really slowly, it will have a slight I reckon curve, something ah . .
156	Shaun	(??) linear – line (hand rises along a shallow slope) – like a straight line that's curved (hand sweeps up).
157	Mark	A straight line . . oh . . yeah.
158	Shaun	Like a constant acceleration (gestures a gentle slope upwards).
159	Mark	Yeah.
160	Shaun	(He points to a blank graph display on the screen.) Like – what's that – how many seconds is that? (Shaun counts divisions along time axis in air.) Five. . . I'd say about a minute (??) a minute thirty to get to the top temperature . . . surely it's got a highest temperature. [Shaun apparently makes a comparison with the previous curve, and estimates it will take more of the five horizontal divisions to reach its peak.]
163	Mark	(He reads aloud as he writes.) "It will take longer because the heat is not as direct . ."
164	Shaun	(looking to Mark) as thermal . . thermal contact . . (?) thermal contact with water.
165	Mark	(?) (He finishes writing.) Alright . .
166	Shaun	Now (???). (He reads aloud as he writes; Mark waits for him to finish, puts the sensor in test tubes then goes to the tap for hot water) . . . (He reads from notes.) "I think that the slope won't be very steep, it will take longer because the sensor isn't in thermal contact with the water."

In line 160 Shaun pointed to the blank graph display to help quantify his prediction. The apparatus handled in the setting up stage was thus referred to in the prediction stage. Both stages progressed in parallel (for example, lines 152, 153) throughout the 36 lines of speech, after which they began the third stage of collecting data and observing. This passage illustrates the students' collaborative prediction stage that networked dyads with reading and writing POE notes; also the setting up stage which networked dyad, apparatus and monitor; and on this occasion the linking of the two (Figure 4.1).

4.1.1.2 Observing, Analysing and Explaining

The POE approach that featured strongly in the prediction stage provided a framework for the lessons, but was not the focus of interest in this study per se. The interactions that were of principal interest took place during the next three stages of observing, analysing and explaining. Specifically, they were the student-student-display interactions. The transcripts showed that these stages frequently overlapped during lengthy experiments, and the network relationships for these stages as shown in Figure 4.1 are incorporated into a single network in Figure 4.2. Individual students are shown as A and B. Opportunity was taken here to include the occasional interludes by teacher and other dyads, and students' recourse to results from prior experiments, worksheet data, and common knowledge, which were not identified in Figure 4.1. The third column illustrates the network relationships that commonly occurred between the actors at each stage. The boldness of the type indicates the significance of the actor. The thickness of the arrows indicates a judgment made as to the frequency of the flow of information from an actor, or attention given to an actor. Arrows indicate speech, reading, a gesture, viewing, writing, feeling, or sending as an analog signal.

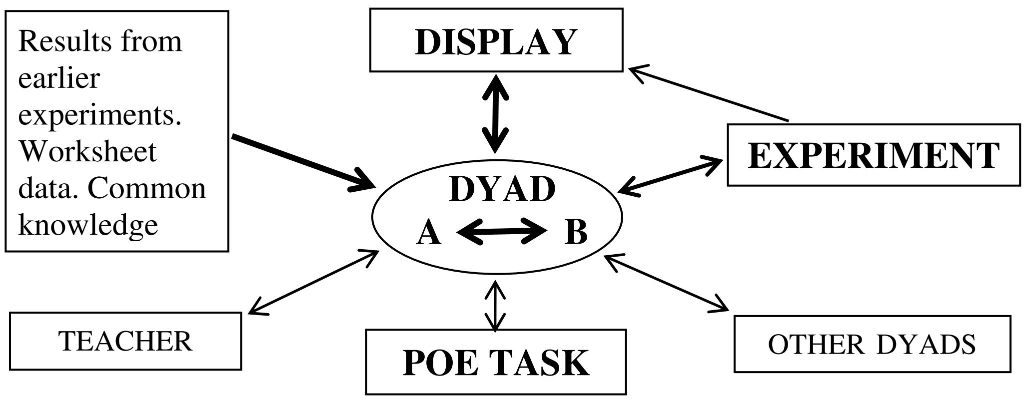


Figure 4.2. Interactions during data collection, analysis and explanation.

In recognition of the broad scope of what constitutes nodes in a network (Bigum, 1998b; Roth, 1996) note that the box *Prior concepts, recent other experiments, previously concluded theory* in Figure 6 has been added to the network relationships shown in Figure 5. As will be shown in the next section, students introduced a wealth of mental models, skills and background knowledge to tasks that shaped their developing understanding.

Diagrams similar to Figure 4.2 have appeared in the literature. A diagram of "pathways of computer entrée into conversation" by Kelly and Crawford (1996) showed bi-directional arrows between computer and students, and between students, as seen also in Figure 4.2. These pathways were central to Kelly and Crawford's analysis of ways by which the computer display entered students' conversations. A similar diagram was presented by Lidstone and Lucas (1998) showing students' interactions with the computer display while using an interactive multimedia program. The present study extends the scope of interactions beyond the students and computer display, by incorporating interactions between dyads and those involving the teacher.

Lidstone and Lucas (1998) characterised one pattern of student-student-display interaction as "mediated collaboration," defined as students pursuing "a common agenda which results in longer and more focused discussions . . . their joint interactions with the program serve to initiate, sustain or inform such discussion . . . interaction is dependent on the program to initiate and/or sustain discussion" (pp. 10, 11). Mediated collaboration equally describes the majority of interactions involving students, MBL apparatus, and the display.

Examples that follow, taken from the student transcripts, show iterative cycles of shared observation and analysis of the experiment and display, and drawing conclusions. Iterative cycles were more common when experiments were extended in time and while the graph lines evolved. The examples also illustrate how students touched the display, felt and adjusted the laboratory apparatus, left the room to consult with the teacher or other dyads, searched data tables, and called on prior concepts to interpret graphs.

The dialogue in many of the following transcripts must be read in conjunction with the contemporaneous computer display, and in these cases a small copy of students' actual graphs appears to the right of the transcript. The essential feature of the small copies lies in the graph shape, which is discernible, and not in the printed characters which in general are not discernible. A large-sized sample of the screen display appears in Figure 4.3.

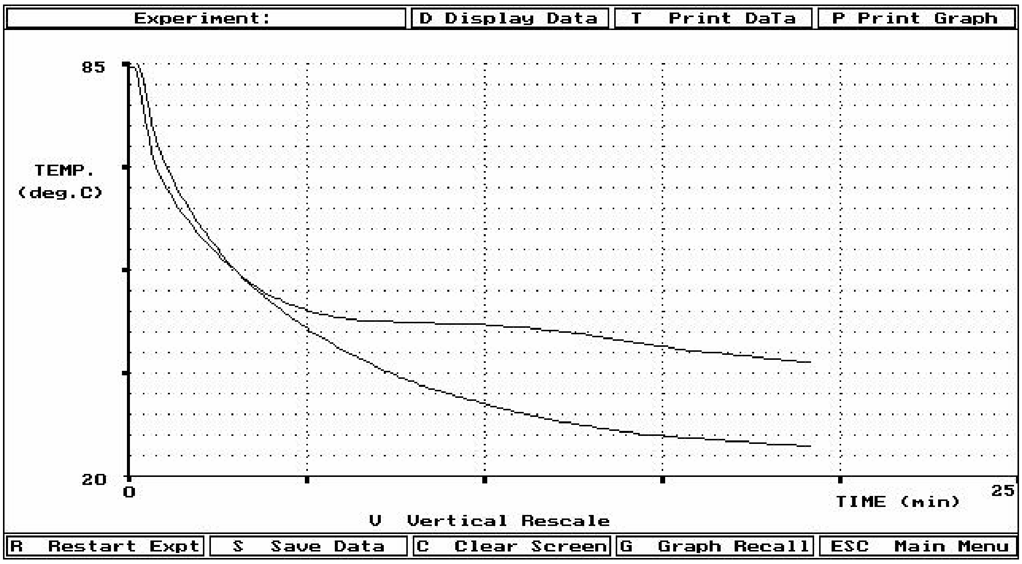
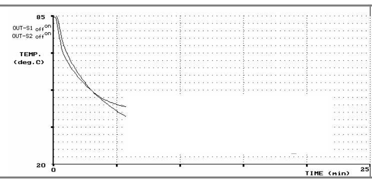
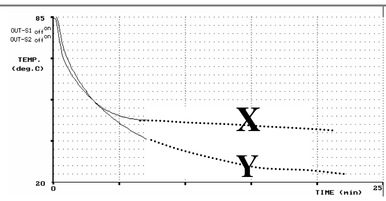
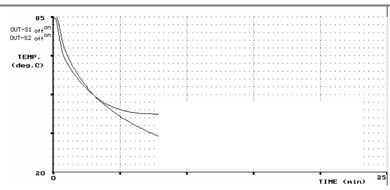
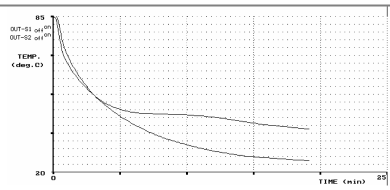


Figure 4.3. The essential feature of this sample screen display, showing two temperature graphs lines, lies in the graph shape rather than the text.

The following extract illustrates the iteration of the last three stages of Figure 4.1: observing (to include describing, touching and adjusting apparatus); analysing (to include assessing, extrapolating, hypothesising and referring to notes); and explaining (to include drawing conclusions and recording). An additional column with annotations "O" (observing), "A" (analysing) and "E" (explaining) has been added to the original transcripts, to show where these three stages appear in the dialogue, based on judgments made by the researcher. During this seven-minute passage the students watched as test tubes containing melted pentanol and lauric acid cooled in the air.

411	Mike	(Both examine the screen.) Not what we were expecting.	O A	
412	Ivan	Which one's which?	A	
413	Mike	Number 2's 46 (i.e. degrees) at the moment (Mike traces a cable back from test tube to interface) . . . Number 2's (lauric) acid. . .	O	
414	Ivan	So number 2's still high	O	
415	Mike	the lauric acid	O	
416	Ivan	but it dropped really dramatically then curved out.	O A	
417	Mike	Yeah . . . That's probably how it's (the lauric acid) going to be (reaching towards the screen) along there (his hand against	A O	[X and Y have been added to the original screen display]

		screen extrapolating how the lauric acid line will grow horizontally – X) and this (pentanol line) is probably going to be a straight down (drawing with his hand a curve dropping quickly - Y) (= Yeah)	A	
418	Ivan	(= Yeah) . . . You see it's starting to solidify on the bottom (as both look at the test tube of lauric acid)	O	
419	Mike	Is it?		
420	Ivan	Yeah – see – the white stuff (Mike looks closely; Mike: = Yes) So that might be why it's starting to . . see (pointing to the screen) if you look at it now it's angling across the curve (Mike starts to write notes. Then Ivan starts to write, consulting screen.) . . . (?) (Ivan gets up, taking coloured pens from his pencil case to draw a colour-coded graph in his notes) . . . (Mike turns the page to write lauric acid notes. Ivan yawns and stretches. Mike turns on the fan to cool the room.)	O A O E O E E O	 Ivan writes in his POE notes: "Pentanol cools at a very steady rate because it does not change state" Mike writes: "(Pentanol) follows a path hyperbolic in nature"
421 **0940**	Ivan	Help to cool it a bit (i.e. the test tubes) . . . (looking at test tubes) it's starting to go claggy like glue	A O	
422	Mike	You can see the crystals forming round the side (rotating his finger, looking closely at the lauric acid in the test tube). (Mike feels both test tubes.)	O	
423	Ivan	(???) feel warmer now? (Ivan feels both test tubes.)	O	
424	Mike	Yep.	O	
425	Ivan	Hmm . . . (feeling both test tubes, then lifting the sensor out of the lauric acid)	O	
426	Mike	You were expecting it to get stuck in there (i.e., the sensor stuck in the lauric acid).	A	
427	Ivan	Yeah. (Mike views the screen for some time; Ivan writes; Mark yawns; the cooling curve proceeds slowly; Ivan turns the page from pentanol notes to make notes on lauric acid; Mike glances through homework exercises to fill in time.)	O E	 Ivan writes in his POE notes: "Lauric acid has a dramatic change in its cooling rate when it solidifys [*sic*]"

				Mark writes: "The test tube did (i.e. lose heat) not the contents."
428	Mike	It's going steeper just because of the fan (points to screen)	O A	
429	Ivan	(Looking at screen) It's helping it along a bit (Both view test tubes, yawn, fill in time) Oh, what is the melting point of lauric acid? (Reading from POE sheet)	O A	
430	Mike	We'll just have to try it again, and see how it melts (neither has yet associated melting point with the horizontal section of the lauric acid graph)		
431	Ivan	What . . fully, or just ah . . ?		
432	Mike	It starts to melt (Mike looks at screen) . . . 10 minutes [time has passed] (Ivan stands up to stretch legs, looks at clock) . . . . . Room temperature's probably going to be when that levels out (touching screen).	O A	

Mike suggested (line 430) the need of an additional experiment to find the melting point of lauric acid. The teacher audio transcriptions show that two other groups departed from their POE tasks to explore related experiments.

The POE notes of all students reflect the notion that they worked through each of the five stages of Figure 4.1. In the large majority of their worksheet notes, when experiments were completed, students wrote up their predictions and observations, and their written explanations showed evidence of having analysed their results. Only five students left a few sections of their POE notes blank. Teacher observations suggest this was due to their leaving a partner do the writing for them.

Initiatives taken within dyads appeared to be equally shared over time. However, occasionally independent action was taken by one of the students. On such occasions Figure 4.2 could be adjusted slightly, as shown in Figure 4.4. Though conversation outwardly appeared normal, the attention of one student was drawn principally to the display and his partner appeared sidelined.

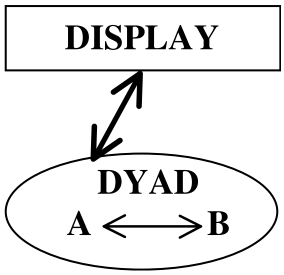


Figure 4.4. Occasionally one student dominates interactions with the display during data collection, analysis and interpretation.

To illustrate, three times during the first lesson Mike became deeply involved with a personal agenda involving mathematical calculations. On the first occasion thirty turns of speech passed (lines 59 to 89, not shown) while he single-mindedly interpreted screen values to calculate a time constant, replying to his partner's distracting conversation with perfunctory short answers. On the second occasion Mike devised a procedure to estimate the time constant, which is evident in the following dialogue.

144	Ivan	So the highest point is (checking the screen) . . . 75.6 [degrees]. (Mike writes this down.)
145	Mike	(Mike continues to write, Ivan tinkers with probe. Mike walks to screen and touches it with pen, examining it for some time.) . . . (He talks as if to himself.) Each of those about a minute. It's probably taken about a minute [referring to major divisions on time axis] . . . 45 seconds to reach the . . . 63 [degrees] . . . (Ivan also examines the screen carefully, while Mike returns to write notes. There is a long pause.)
146	Ivan	So the room temperature was . .
147	Mike	Its probably taken 30 seconds to reach it (continuing to write).

In this episode Ivan was concerned with temperatures (lines 144, 146), while Mike was intent on estimating the time constant (lines 145, 147) and was virtually speaking to himself. Mike frequently operated one step ahead of Ivan, though ultimately their POE notes showed they reached shared conclusions.

This section has thus far identified the actors in the MBL and described the network relationships of their interactions (Figure 4.1). The networks associated with observing, analysing and explaining experiments and graphic data (shown separately in Figure 4.1 and combined in Figure 4.2) show that the medium of the computer display is central to an interactive process involving students. This is in contrast to a picture of learning taking place as a result of unidirectional instruction "delivered" by the medium or an instructor.

The remainder of this chapter seeks to interpret the dialogic interactions between these actors. In each of a number of the sections that follow, the discussion following the analysis presents one or more assertions, each illustrated by examples taken from the transcriptions. A summary of the 11 assertions made in this chapter appears in section 4.5.

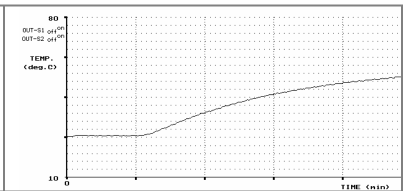
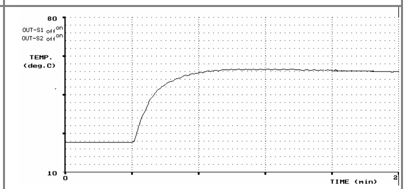
4.2 THE ROLE OF THE DISPLAY IN STUDENTS' DIALOGUE

Graphic objects such as the display may be seen and operated on either as concrete objects in the environment, or as expressions symbolic of other entities (Kozma, 1991). To answer the question "To what extent did students view the display as relating to the experiment or another outside entity, or did they operate on the display symbols in their own right?" attention was restricted to speech and gestures while students viewed the display, and to responses prompted by the display, such as students referring to tables in search of explanatory data, copying screen images, and recording worksheet explanations. Again, the annotated transcriptions of video and audio recordings of the dyads provided the principal data sources. Dialogue prior to the actual start of data collection for each experiment was no longer considered. This was to juxtapose the active display with the experiment in order to find any dialogic relationship between the two.

To determine a suitable unit of analysis consideration was given to the size of the unit. Phrases and sentences taken in isolation often were inadequate to discern if a student was talking about the graph per se, or linking it to the experimental phenomena. The unit of analysis was the turns of speech associated with a single experiment – from the time data collection commenced, to closure of discussion for that episode of data capture. The length of the unit varied from three turns of speech lasting ten seconds, to many minutes of dialogue. Taking the dialogue for a single experiment as the unit of analysis, the question was asked: Did the dialogue show whether students viewed the graph as an isolated concrete entity, or did they operate on the display as symbolic of the experiment (or other external entity)? No distinction was made between members of the dyad, due to their generally close collaboration, as to whether one or both associated the display with an external application. The evidence in reading the transcriptions and POE notes was that the spoken expression of one was taken up by his partner and a common understanding appeared in both of their written notes.

4.2.1.1 Analysis

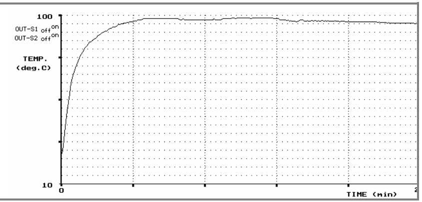
Of the fourteen tasks in thermal physics, eleven were completed by all of the videotaped students, and these were analysed for this section. The videotaped dyads conducted twenty-seven experiments during these eleven tasks. Students viewed the graph as an extension of the experiment in twenty-six of these experiments. In the single exception cited below, the students' dialogue focused solely on features of the graph, with no reference to the experiment in words or writing. However, toward the end of their discussion the teacher perchance entered the room and asked questions about the display. The probe had been inserted into a test tube that in turn was immersed in a beaker of hot water.

201	Teacher	So what's that [graph on the right] telling you?	
202	Shaun	It didn't have much of a thermal contact with the hot water. (Teacher: = Alright).	
203	Mark	If it had of had good thermal contact which it did the first time [as with their previous graph shown here on the right] then the two results would differ very very greatly (Shaun: = Yeah).	

Without hesitation, both students explained the graph features in terms of what happened to the sensor in the experiment. So the evidence was clear, as with all other instances, that the students associated the graph display with the experiment at hand.

The analysis of dialogue revealed seven ways by which the students, while viewing the display, linked it not only to experiments, but also to a number of other conceptual models.

(1) *Students made a direct reference to the experiment.* Ivan, watching as the graph line grew horizontally, expected (line 56) that the line should descend. His reason was based in the experiment: The hot water was losing heat hence its temperature should drop steadily. Mike agreed, but suggested the water would cool rather slowly (line 57).

56 57	Ivan Mike	That's not supposed to be right. . . it's supposed to dissipate its heat but Oh but that's only gradually. It's still hot water.	

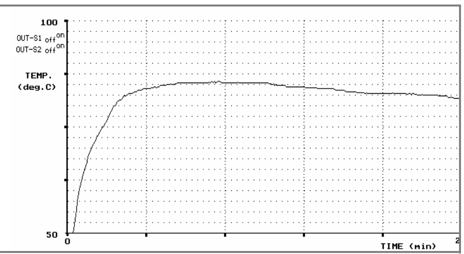
This example was typical of students' commentaries that stated clear links between the display and experimental phenomena. A reading of the teacher audio notes shows that when questioned, students readily explained graphs in terms of the current experiment.

(2) *Students made non-verbal references to the experiment.* Mike and Ivan had inserted a temperature sensor into a copper rod and prepared to rub it with a cloth to warm it by friction.

206	Mike	Start! (Ivan starts the graph, while Mike rubs the rod) . . . (?) the magic (?) now . . . (Both alternate from watching the screen to watching the metal rod.)

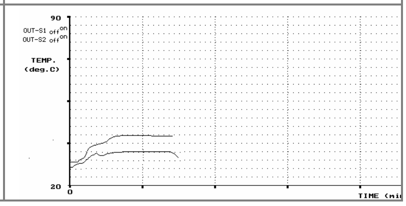
Students frequently looked back and forth between display and experiment without saying a word, sharing a tacit understanding of the cause-effect relationship between the two. On one occasion when the graph line dipped, silence turned to speech: "You're taking it off [i.e., the sensor lost contact with the hot metal block] . . . well don't take it off!" (Dyad B, line 303)

(3) *The unspoken link between graph and experiment became evident only in contemporaneous POE notations.* During one experiment Mike and Ivan discussed the developing graph without making any verbal references to the experiment. In line 19 that follows Ivan read data from the display, then wrote his POE notes.

19	Ivan	It'll go to 60 70 80 up to 100 . . . that's be 75 [degrees] (He touches the screen.) (??) . . . It's started to decrease in temperature now . . . (There is a long pause as both look at the screen. Both turn to writing their POE notes.)	

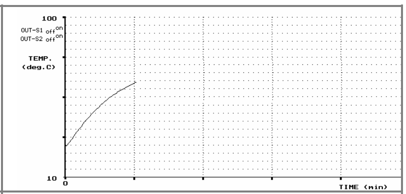
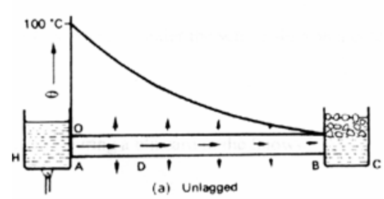
Ivan's observation notes read (written as if he was making a prediction): "The temperature will quickly rise to approximately 80^0C and then very slowly decrease as the water dissipates its heat to the surrounding air." While neither student expressed verbally any link between display and experiment, the salient reference "dissipates its heat to the surrounding air" revealed the relationship Ivan made between the two.

(4) *Students linked the display to tables of data and other background material provided in their worksheets.* David and John had previously graphed the temperature rise of water when they dropped a copper slug into the calorimeter. They followed this by superimposing a second graph for an aluminium slug. The latter line rose to a higher temperature.

908	David	(??) . . Do we – do you want to go higher than 40.8 [degrees] or ? . . .	
909	John	No that's it.	
910	David	OK . . . (Both write, copying the graph). Actually, I think that works in perfectly with our results (turning to the data table of specific heat on page 16 of his notes) because . . .	

David and John made a visual comparison of the ratios by which the two lines had risen (approximately 2:1, as shown in the graph on line 910), with the ratio of the specific heats of the two metals in the table of specific heats (910:390, also in broad terms 2:1). Once groups became aware of the data tables for specific heat and thermal conductivity, they often compared features of graphs with data values in the tables. Students used the data table texts as conceptual entities (Kozma, 1991) quite separately from the actual experiments. The POE notes of many students showed that by the fourth lesson they were using tables of thermal conductivity and specific heat to interpret graphs.

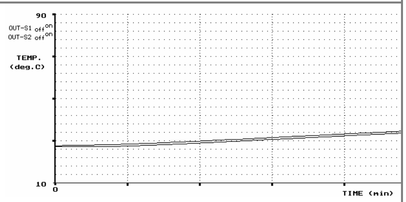
In the next instance, Mike and Ivan viewed a temperature-time curve that reminded Ivan of a homework problem.

105	Mike	It's more like a straight line curve. (First minute has passed.)	
106	Ivan	Yeah. Actually there was something on that piece of paper [notes given out in the introductory lesson]. Where is it? (Ivan looks for his notes.) It's called a . . (looking at homework problems on page 7).	
107	Mike	It is that test tube thing? [i.e., a diagram in the notes of a rod with a test-tube appearance, shown on the right].	

108	Ivan	It's called a "lag test" (looking at Q. 5). (Both write at length, looking back at the screen) . . .	

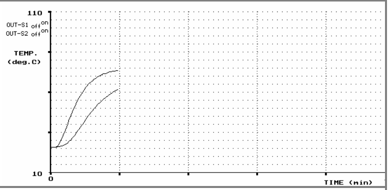
The "lag test" problem bore a superficial similarity to the experiment, featuring the use of insulation, the process of heat loss, and a curved graph. Nothing came of this idea, yet it illustrated the broad scope of associated concepts students drew on while viewing the display.

(5) *Students linked graph features with the characteristics of the MBL apparatus and the user.* Some occasional graphic features were artefacts of the sensors, hardware or software, and are ubiquitous to MBLs. The students distinguished between these and experimental data intrinsic to the experiment. One feature was the error margin of the sensor. When David and John heated two identical blocks of metal with similar electrical heating elements, the temperatures rose at slightly different rates. While there were a number of physical reasons for the difference, David's last remark (line 1053) showed the link he made between graph and sensor limitations.

1051	David	So far so good . . .	
1052	John	The first one's getting up further [i.e., Number1 sensor is higher than Number 2 sensor].	
1053	David	That's right because that one was – you know – 0.1 degrees ahead to start with, the margin of error to start . . . Yes the error's – ah – up to 0.2 because that's the margin of error that sensors have [i.e., 0.1 degrees].	

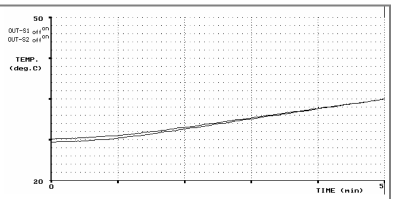
(6) *Students associated the graph with other concepts not provided in the source materials.* As shown thus far, students linked the display to the experiment, data tables, and sources of experimental error. They also attempted to link the graphs with other concepts drawn from their background knowledge.

In the following excerpt David and John were heating aluminium and iron rods dipped in hot water, and the heat was transferred to the sensor inserted in the top of the rods. John drew a comparison between their rates of temperature rise and their densities.

461	David	(He points to screen, then helps to trace cable.) OK aluminium's ahead in k's [i.e., kilometres per hour].	
462	John	Aluminium's the best of all (both laugh at the contradiction to their predictions).	
463	David	And we had it as one (John laughs) . . . . (as both view the screen carefully).	
464	John	Aluminium's not as dense as iron . . it's real light.	

In line 464 John suggested "aluminium" rose faster than "iron" was because it was less dense, though they never followed through with this idea. A reading of students' POE notes showed that students linked graph shapes variously with: density of the material, atomic size, surface area, and a notion that some metals can preferentially "retain heat" better than others. These concepts, some of which were inappropriate in terms of canonical science, became the subject of a teacher-led discussion in a follow-up lesson.

(7) *Students applied mathematical treatments to the graph per se.* During the fourth laboratory session Mike and Ivan heated two identical metal blocks with matched electrical elements. This was the same experiment that David and John had conducted (see (5) above), in which they associated the display with sensor error margins. Mike responded to the display differently, as shown in this excerpt.

961	Mike	It's kind of a straight line (running his hand back and forth along the line) . They're going up . . that's what it should be. (Ivan: ????). That's here on the third [day's work-] sheets. . . that's [the table of] specific heats. (The teacher enters; Mike addresses him.) We were just saying that the specific heat . . (Ivan: = Data) (= it) should make it a straight line (angles hand up in line with screen display). It . . it shouldn't be too curved.	
962	Teacher	So that the specific heat – there's a linear connection (Mike: =Yeah) you're saying between energy put in, and temperature rise – is that what you're saying?	

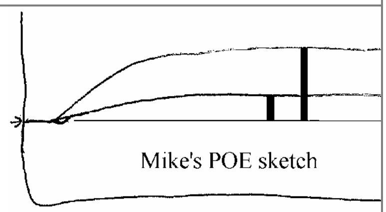
963	Mike	Yes. We're saying heat 470 Joules to raise 1 kg over 1 degree, (Teacher: = Yes) and that should be fairly constant I think	

In line 961 Mike said of the straight line "that's what it should be." Apparently Ivan asked Mike his reason, because Mike then referred to the specific heat table in their worksheets. In lines 961 and 963 Mike explained that the constant rate of energy given to the metal slugs should cause the line to rise at a constant rate. While Mike linked the display to data tables, he used the data to give the graph a mathematical meaning, that is, it featured a line of constant gradient.

A number of similar instances showed the linkage students made between the display and mathematical formulae and concepts. For example, David and John (as described in (4) above) examined the ratios of graph maxima. A reading of student POE notes and teacher audiotape transcripts showed that many students treated graph shapes from mathematical perspectives: They described curves as straight, hyperbolas, concave up, and concave down; they compared slopes; and in one case they likened temperature graphs to parabolic acceleration curves (Sony and Mark, Dyad B).

Students associating mathematical formulae with the display merits particular attention. When students were presented with graphs which they realised could be treated by some mathematical analysis, their perception of the display seemed to shift from treating it as a symbolic expression (say of the experiment) to that of a concrete object in its own right. This is a natural process encouraged in physics students. Students analysed graphs to find ratio of slopes and temperature changes, and to calculate time constants and specific heats.

In this account, Mike and Ivan had superimposed graphs of water in a calorimeter heated by 50g and 100g blocks of iron taken from a hot water bath. They were trying to compare the heat energy each block transferred to the calorimeters.

645	Ivan	Because the mass was doubled wouldn't the heat energy stored be doubled? Unless the equation has a square root or something.	
647	Mike	Well it looks like its something squared, because that one's raised so much above that line (moving his horizontal hand from one level to another). (Ivan: (going to screen) = Yeah) like it's gone up three or four times.	 Mike's POE sketch

Mike considered the possibility of a square law by comparing the two vertical increases, since one appeared to rise four times the height of the other, with only double the mass. (The graphs were indeed not actually comparable due to flaws in their experimental procedures and they eventually changed this line of thought.) Though the teacher had suggested the task exercises were primarily intended to be qualitative, Mike became quite involved with his calculations.

1074	Mike	Yeah heat energy Q added to or lost by . . it's $(t_2 - t_1)$ (partially quoting from p.16 formula below the table). (Mike thinks about this) . . . $mC(t_2 - t_1)$ . . . (He turns to the screen and points.) So we could work it out there if you had to . . .

He and Ivan spent the best part of 45 minutes during Task 10 calculating the specific heats of aluminium and iron, and finding verification for the formula $Q = mC(t_2 - t_1)$ from the display. The graph display had become the de facto object of analysis. These students were interpreting the display in a manner central to the practice of physicists. They were becoming adept at interpreting graphs both qualitatively and quantitatively for their intrinsic meanings, quite separately from their association with the experiments.

Sometimes the distinction between treating the display as a symbol, and manipulating it as a graph in its own right, became blurred in students' dialogue. When graphs were superimposed they often spoke in terms of "aluminium" or "iron" to distinguish between the lines: "Iron is climbing a lot more rapidly than aluminium . . . It's a dramatic change" (Ivan, line 989). "Iron" may have referred to the graph line or to the block of metal, or somehow to a fusion of both. The students appeared to be addressing the graph in its own right, while seeing in the graph the reality sitting on the bench.

4.2.1.2 Discussion

> Assertion T1. Students viewed the display (a) predominantly, as representing the experimental phenomena, (b) as associated with other conceptual models related to the experiment, and (c) as a graph in its own right. (The symbol "T1" stands for "Thermal physics, Number 1 (assertion).")

The role of the display in the students' dialogue began with the question: To what extent do students view the display as having a referent in other domains, or do they operate on the display symbols in their own right? The significance of this question is signalled by Kozma's reminder, "the extent to which objects refer to other domains, and thus serve as symbols, should be explicitly addressed in research with symbolic environments" (Kozma, 1991, p. 206). The object in this case is the electronic trace of a graph on a computer monitor. Graphs play important roles in the repertoire of physicists, and are one of many conceptual models used to facilitate comprehension of the natural systems of their world. Conceptual models, as defined by Greca and Moreira (2000), are "external representations that are shared by a given community . . . [and] can materialize as mathematical formulations, analogies, or as material artifacts" (p. 5). Arguably, tables of physical data are included in the latter. In this section all of these – graphs, mathematical formulae and tables of data – have been seen to enter student dialogue. Students used all of these to make sense of realities, such as the passage of heat energy through materials, measuring the "hotness" of bodies, or the process of change of state when a body cools. The realities are closely associated with, but not necessarily visibly evident in, the experiment.

The analysis found that in all twenty-seven experimental episodes analysed, the students associated the graph display with the experimental phenomena such as temperature changes in objects, characteristics of metals, and the effects of insulation on cooling. As David and Stefan said in interviews,

> It was easy to explain things because we had a graph sitting in front of us. . . . you could directly relate to the graph and say: This point here is the maximum point, where it had reached the ambient temperature, or whatever had been going on in the experiment. (AS1081099; see Appendix 9 for the coding of interviews)

> You could actually see it, the graph, and you could just imagine it a bit more, how the temperature was going, and how the object was heating up. (AS2071099)

Depending on the dyad and experiment, students associated the display with data tables, formulae, textbook diagrams, and graphs from other domains of physics. Many, but not all, of the conceptual models proved relevant to the task questions.

Some of the students proceeded to a further stage, operating on the graphs in their own right. The nature of their inquiries provided answers to mathematical questions rather than phenomenological explanations. Physics students need to become adept at interpreting graphs both qualitatively and quantitatively for their intrinsic meanings.

4.3 THE LEVEL OF STUDENT-DISPLAY INTERACTIONS

This section examines the depth of interaction between student and display during and following data collection. A review of the video recordings provided evidence of a wide scope of cognitive interactions with the display and the task at hand. These ranged from students appearing tired and disengaged, to a level of curiosity that promoted "what if?" speculations. Further, a reading of transcriptions confirmed observations made by the teacher during the four lessons, that students revealed a variety of activities during data collection – a contrast with the pilot study of kinematics, where data collection was brief, and student analysis was retrospective to the experiment.

The strengths of interactions pictured by heavy and light arrows in Figures 4.1 and 4.2 reflect a judgment made as to the frequency of the interaction, for example, between student and student, or student and display. This section examines the intensity of interactions brought to the experiments by students. A low intensity approach is taken by a student who does only sufficient to fulfill basic task requirements. Intense application typifies a student who reflects on an experiment, and builds on understanding from earlier experiments to construct new knowledge. One categorisation of how students go about their academic tasks is the deep versus surface approach to learning (Chin & Brown, 2000; Hogan, 1999). A deep approach to learning is characterised by intrinsic motivation, and actively manipulating information with a focus on understanding and integrating knowledge. In contrast, students taking a surface approach do not reflect on the purpose of tasks and fail to associate the details with other meaningful schemata. Hogan's (1999) study of the depth of sociocognitive processing of small groups' science discussions, and Chin and Brown's (2000) comparison of deep and surface approaches – both with triads of Grade 8 physical science students – are two of the few applications of the depth-of-processing construct to science education reported in the literature.

Chin and Brown (2000) analysed the discourse of small groups engaged in classroom discussions and laboratory activities. Classroom discussions covered such topics as the nature of matter, change of state, and physical and chemical changes. Laboratory experiences included separating salt-sand mixtures and plotting temperature graphs. From their analysis emerged categories that illuminated and were capable of describing differences between deep and surface approaches to learning. The nature of the student tasks and topics of discourse bore certain similarities to the present study. Chin and Brown suggested that deep thinking processes may be enhanced by the kinds of activities essentially embodied in a POE approach.

The characteristics of surface and deep approaches as described by Chin and Brown were extracted and tabulated as a starting point for the present analysis. Some features of the original table that were not identified in the data during the analysis stage were deleted to provide the more succinct listing that appears in Table 4.1.

Table 4.1

Summary of Dialogic Instances of Surface Versus Deep Processing of Ideas

Category	Level	Instances in the dialogue
Nature of students' explanations, actions	Surface	"I don't know" and stop Simple observation, with no explanation of cause Reiterate observations Read screen data, make an estimation Refer to a graph feature Measure a value, make simple calculation Give directions while viewing screen
	Deep	Elaborates on a specific example Make a prediction (during or after observation) Cause-effect relationships Construct or reconstruct explanations Judge a feature of the graph Draw comparisons Use the screen as a working diagram Extended calculation or estimation Appeal to graph to support a claim
Asking questions	Surface	Ask about a procedure
	Deep	Wonderment, curiosity, puzzlement Elicit further inquiry
Meta-cognitive activities	Deep	Self-evaluate ideas by expressing understanding, failure, impasse, value judgments
Approach to tasks	Surface	Talk at procedural, observational level
	Deep	Search for alternative data source to support answer

4.3.1.1 Analysis

A total of nine experiments taken from Tasks 1, 3, 7 and 10 was selected for analysis as it was felt these represented a suitably large cross-section of laboratory activities. Mike and Ivan (Dyad A) were videotaped completing all of these tasks. Mark and Shaun were recorded on Day 1 (Dyad B), and David and John during Days 2 to 4 (Dyad C). The transcriptions of video recordings were read for instances that matched two criteria: firstly, speech when students were viewing the display; and secondly, speech that matched the instances of dialogue in Table 4.1. The first criterion meant that the analysis would focus on student-student-display and teacher-student-display interactions. Each match was recorded as an instance of a deep or surface approach, in a table that included student name, task number, line of speech, and the spoken passage. The numbers of instances of deep and surface processing of ideas for each student were then totalled, to allow comparisons within each dyad, and are presented in Table 4.2. The class rank of each student was also included, based on the total of his assessed marks to date for the academic year.

Table 4.2

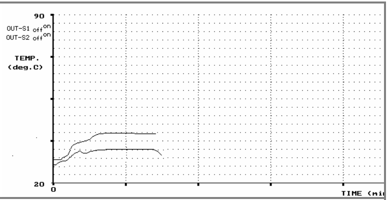
Frequencies of Surface and Deep Approach Expressions by Students Viewing the Kinematics Displays

Dyad	Student ID	Student's academic class rank (*n*=15)	Frequency of surface approach	Frequency of deep approach	Ratio of frequencies of deep to surface approaches
A	Mike	3	26	51	2.0
(Days 1 to 4)	Ivan	10	25	25	1.0
B	Mark	14	16	17	1.1
(Day 1 only)	Shaun	13	16	19	1.2
C	David	8	12	16	1.3
(Days 2 to 4)	John	5	19	5	0.3

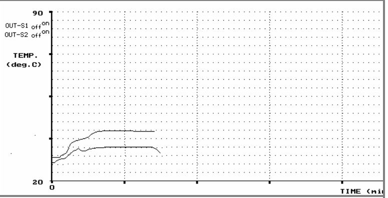
Surface approach comments are not unimportant, for they interchange necessary and vital observational and procedural information, data values, simple questions and the like. However, deep approach comments encompassing insightful explanations, expressions of puzzlement, self-evaluations and deeper processing of data may be taken as indications of a higher degree of intellectual involvement with the tasks at hand. There is no clear-cut division between the two levels of operation; rather, they form a continuum (Hogan, 1999). Neither should the totals columns be misinterpreted as tallies of turns of speech, which do not characterise depth of processing (Hogan, 1999). The significant feature of Table 4.2 is the ratio between deep and surface approaches, shown in the last column. The table shows that four of the six students expressed themselves fairly equally at both levels. The outlying students were Mike and John.

Mike expressed himself at the deep level about twice as often as his partner Ivan. Both shared similar class academic ranks, which prompts the question as to what different characteristics Mike brought to the tasks. A careful review of teacher notes, videotapes and speech transcriptions provided a profile of his laboratory activities. Mike was a student who started experiments quickly and confidently, at times bypassing the prediction stage. He led initiatives, such as suggesting additional experiments or selecting mathematical procedures to process data. In response to questions raised by the teacher, Mike responded three times more frequently than Ivan. Mike found puzzles hidden in the data and often meditated at length looking for solutions. He tended to work independently of his partner when pursuing an idea. Some of his ideas were incorrect, and his inexperience with laboratory techniques cost time and led to repeating experiments. However, as noted by Chin and Brown (2000), correctness or canonical understandings are not prerequisites for deep processing. Both Mike and Ivan expressed themselves comparably and competently in their POE notes.

By way of contrast with Mike, John (Dyad C) was very sparse with comments at the deep level. Yet academically he ranked alongside Mike, and somewhat higher than his partner David. Teacher notes, videotapes and transcripts support a description of John as showing limited initiative, somewhat diffident, adding very little by way of original contributions to the dialogue. He waited until the last half of the fourth lesson before proposing an original experiment. The following passage from the third lesson illustrates how John expressed himself at a surface level. Both students had spent some time examining tables that showed the specific heat for aluminium was about double that of copper. They then dropped equal masses of aluminium and copper into two calorimeters each containing 100 ml of water. The graphs showed the rise in temperature of the water heated by aluminium was about twice that of the water heated by copper.

910	David	OK . . . (both write, copying the graph). Actually, I think that works in perfectly with our results (turning to the specific heat data) because . . hold on.	
911	John	(His head is buried in his writing) Not really . . you don't know . . (looking up at David) you can't really predict.	
912	David	Yeah but	
913	John	which element's gonna . . (= and by) (David: = I mean) how much	
914	David	Yeah you can't predict how much but	
915	John	unless you are an Albert Einstein. [It is hard to interpret John's frequent smile.]	

David (line 910) drew to John's attention the relationship between the specific heat data and the temperature rises of the graphs. John's adversarial response (line 911) was dismissive of David's claim, though he proffered no reasons. He missed the opportunity to contribute to a fruitful discussion about the graph meaning. Nevertheless, David went on (line 916) to elaborate on the connection between the graphs and the table of specific heats.

916	David	It'd be interesting to try if we had a 50 g piece of stone because if stone was like 40 – 40.6 [degrees maximum, like aluminium] or so then we would know our results were pretty much spot on [since the specific heat of Aluminium is 910, and stone is 900], because all the others are all (?) proportions (gesturing by hand a series of levels). (John fiddles with tongs, as he does throughout many of the discussions.)	
917	John	(John ends the graph and saves it.) OK. (John empties the calorimeter and returns the aluminium block to the water bath. David sits and thinks.)	
918	David	And so how can we explain this? That, umm, . .different materials take different amounts of heat energy to heat them,	
919	John	Yeah (John clears the screen and sits)	
920	David	but once at the same temperature, the extra heat energy is still there? . . and, it heats the water to a higher temperature?	
921	John	(He seems either very indifferent, or he is quite tired.) I don't know (as he flicks over a page of notes) . . . (He starts to write his explanation, along with David. Though John appears tired or indifferent he writes quickly and refers back to the specific heat table.)	

David suggested (line 916) that if an experiment using stone gave the same result as for aluminium, then his explanation that temperature rise was proportional to specific heat would be verified. John had been working for fifty minutes now, and the videotape gave the impression that he "seems either very indifferent, or he is quite tired" (line 921), which could explain his lack of involvement. Though his prediction for this experiment had been wrong, John went on (end of line 921) to write a lucid explanation in his POE notes: "different materials have different heat energies . . . " that mirrored David's words in line 918. The teacher's diary notes about John's passive manner ("John rarely initiates or volunteers any conversation") at the time suggest that he may have preferred traditional laboratory procedures (aim, apparatus and procedure prescribed in detail) or a lecture format. A constructivist approach is not received well by all students (Tsai, 1999). However, during a later interview John assured the teacher that he preferred the POE format, and in a written questionnaire completed after the fourth lesson he wrote very positively about the value of inter- and intra-group discussions and being forced to think through the prediction-explanation format.

The data in this analysis includes responses to twenty questions posed by the teacher, framed to probe students' understanding, such as "So what's it telling you about the copper and the iron?" and "What have you concluded from this?" Replies by the videotaped students to all but one of the teacher's questions reflected deep approach responses.

As mentioned at the start of this section, a different aspect of the level of students' involvement became evident during the actual experiments. This had not become evident in the pilot study of kinematics (see section 3.5), for the obvious reason (seen in retrospect) that those experiments lasted only a few seconds. Thermal experiments extended from 30 seconds to 25 minutes, during which time the computer logged data that transferred to an evolving screen graph. An analysis was made of the types and levels of student activities during these periods.

For the six students videotaped, student time off task was only a few minutes of the total 206 minutes actually logging data. As some students said in interviews, their occasional visits to other dyads to exchange ideas provided refreshing diversions, and even then these were not social excursions; they remained consistently focused on their laboratory tasks. For the major part students watched graphs grow alongside experiments, meditated, copied graphs, wrote POE explanations, and read the task to follow; but principally they engaged in dialogue – primarily with their partner, but also with the teacher and visiting dyads. The dialogue was analysed and compared with the instances of surface and deep thinking described in Table 4.1. The majority of instances in the table that matched the dialogue were those of deep mental processing. The numbers of occurrences of deep thinking from most frequent to least frequent were:

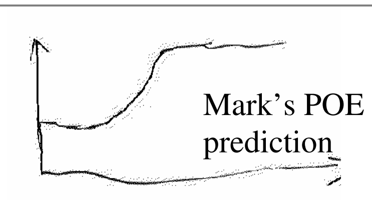
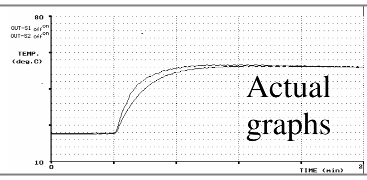
- Using the screen as a working diagram (22)
- Constructing or reconstructing explanations (18)
- Judging a feature of the graph against expected criteria (15)
- Predicting, with reasons, how the graph would develop (14)
- Appealing to a graph to support a claim (14)
- Self-evaluating ideas by expressing understanding, failure, impasse or value judgments (13)
- Making an extended calculation or estimation (10)
- Explaining a cause-effect relationship (9)

- Searching for an alternative data source to support an answer (7)
- Drawing comparisons with another graph or table of data (4)
- Expressing wonderment, puzzlement or curiosity (3)
- Eliciting further inquiry, such as proposing a further experiment to support a claim (3)

It is important to stress that these instances appeared in dialogue during the actual course of data logging, which constituted about 40% of laboratory time. Following data logging students spent additional time viewing, discussing, analysing and writing in front of the display.

A different approach to the analysis was to examine extended interchanges of dialogue, to assess the depth of sociocognitive processing (Hogan, 1999). The transcripts were read as blocks of speech, each block corresponding generally to a single experiment during and immediately following the data logging stage. These multiple turns of speech revealed how groups perceived their tasks, their level of tenacity at finding answers to their questions, and their styles of interaction.

The videotaped dyads conducted 18 experiments, and in 17 of these both students expressed themselves at a deep level in their exchanges of dialogue. The one exception was the first experiment conducted by Mark and Shaun. Mark stopped the experiment after 30 seconds before Shaun could respond. They repeated the experiment when Shaun pointed out that Mark had misread the task. The following is an excerpt from their second attempt at this experiment. They had plunged two temperature sensors into hot water, and the graphs rose sharply before flattening out.

84	Mark	Yeah, that's convex, that's concave - I thought it might have been the other way (sweeping his hand upwards). [Note Mark's prediction on the right, compared to the actual graph on the right of the following line].	
85	Shaun	(???). Now we've got to explain why. We've got to explain why it's done that.	
86	Mark	Ah because (reading as he writes) "because the sensors were placed in a sudden change of temperature, instead of gradually heating it up" . . .	

87	Shaun	Yeah (looking at screen). . . Why is this SHAPED like that - that's what we've got to try and explain.	
88	Mark	Because like (holding the sensor) substances instead of . . like . . gradually heating up (Shaun: ?) . . If you put it in your hand it (= will go up) (Shaun: = it'll go slowly), if you put it straight into hot water it will go fast. (Mark continues to write his thoughts.)	
89	Shaun	Yeah but you've got to explain why is it CON – VEX . . .	
90	Mark	Because I just told you SMARTIE.	
91	Shaun	Ah . . it's alright. What is that (pointing to Mark's notes). What're you doing?	
92	Mark	A curve.	
93	Shaun	(???). (He makes mock criticism of Mark's notes. Mark takes his work with a serious expression, while Shaun smiles rather frequently, though he too is serious with his work.) Ah THE curve.	
94	Mark	(He reads his finished Explain section of the POE.) "The curve of graph was more convex than it was concave, because the sensors were placed in a sudden change of temperature, instead of being gradually warmed up." (Both continue to write.)	

Both students clearly understood they had to interpret the shape of the curve (which contrasted with their predictions). Shaun tenaciously stressed they needed to explain <u>why</u> the curve was so shaped (lines 85, 87 and 89), and with good-natured banter Mark constructed his explanation (lines 86, 88 and 94). Both students expressed self-questioning statements (lines 84, 85 and 87).

The teacher frequently heard similar interactive exchanges as he circulated from dyad to dyad. Though not possible to quantify, teacher observations and POE notes support the notion that dyads generally (a) had clear perceptions of the predict-observe-explain demands of their tasks, (b) displayed intellectual curiosity and tenacity in completing them, and (c) displayed co-constructive styles of interaction. The three members of Group E ranked lowest academically in the class, and while they did not complete as many experiments as the other groups, two of the members wrote very insightful (though at times incorrect) explanations.

4.3.1.2 Discussion

> Assertion T2. During student-display interactions, while students' activities ranged from fulfilling basic requirements to deep level cognitive processing, the dyads completed the majority of tasks at a deep level of mental engagement.

This section analysed the depth of students' on-line processing of observations and ideas. The primary analysis was based on characteristics described by Chin and Brown (2000), using transcripts of students' dialogue while interacting with the computer display. It found that the students' approach to tasks ranged from surface to deep levels of cognitive engagement. The latter level was viewed as desirable, indicating students' capacity to analyse critically laboratory phenomena, and assimilate new insights into their existing beliefs. The dyads completed the majority of their tasks at a deep level.

While all videotaped students expressed themselves at a deep level, as individuals their frequency of deep level expressions varied considerably. Mike expressed himself extensively at a deep level. He was a leader, confident, inclined to answer quickly, and aroused by puzzles. John's sparser use of deep level expressions reflected his less conversational and more retiring nature. Yet both he and Mike expressed themselves at a similar level in their written notes, showing a high level of insight and reasoning. These observations are supportive of the study by Chin and Brown (2000), who concluded "students' learning approaches are more differentiated than can be denoted with a bipolar deep-surface distinction" (p. 132). Nevertheless, the distinction in the present study is useful. It establishes that in the context of the MBL, physical phenomena were displayed in a manner conducive to deep learning approaches in the laboratory. Especially was this evident when the teacher prompted students to extend their explanations.

The analysis also evidenced a deep approach at the sociocognitive level. Students responded to their assigned tasks by cooperating at intra and inter-group levels, and talked through procedures, ideas and conclusions.

> Assertion T3. Students' deep approach to learning was supported by the enduring nature of the display.

While Assertion T2 contends that the display was supportive of students' deep approach to learning, this capacity was enabled by the enduring nature of the display. The display initiated, maintained, and became a focal point of dialogue in the MBL. Recalling that a criterion for the analysis was that students were viewing the display during their dialogue, then the enduring nature of the display was an adjunct to, and promoted, students' deep processing of ideas. Previous research has associated the endurance of screen representations with maintaining conversational cohesion (Roth, Woszczyna, & Smith, 1996) and increased student activity, such as generating more concepts and propositions, during tasks (Nakhleh & Krajcik, 1994).

> Assertion T4. During data logging, dyads generally engaged in multiple on-task activities related to making meaning of the graphs.

An important aspect of this part of the analysis was to create a record of how students used their time with thermal physics. This assertion acknowledges that students used data logging time fruitfully. In contrast with a pilot study of kinematics experiments, in which data collection was completed in seconds, thermal physics experiments extended from 30 seconds to 25 minutes, meaning that graphic information was not delivered almost instantly, but rather as a slow process of growth. Of the 133 occurrences of deep mental processing (Table 4.2), it is important to remember that these instances appeared in dialogue while students viewed the display, and that actual data logging constituted about 40% of laboratory time. Students' thought processes were able to keep pace with or advance ahead of the graph, as evidenced by their (a) using the screen as a developing working diagram, (b) progressively constructing or reconstructing explanations, and (c) predicting how the graph would develop. Students were afforded time to adjust sensors and equipment and see time-delayed responses on the display. They observed changes of state, touched warm objects, and referred to data tables against which to judge their understanding of graphs. In other words, they worked the experiments from the inside, not from the outside, as it were, as the experiments unfolded. They were able to confirm predictions, settle divergent views, section off and analyse stages of the graph 'on the run', and forecast future sections. Using two sensors allowed for time-evolving comparison studies.

The next section of this chapter presents an interpretive analysis of student-display interactions and how the display mediated their understanding.

4.4 STUDENT UNDERSTANDINGS MEDIATED BY THE DISPLAY

To introduce this section, some pertinent findings discussed in the literature review are restated:

1. MBLs assisted students to interpret graphs (a) by grounding the graphical representation in the concrete action of students controlling the experiment, (b) by

the inclusion of different ways of experiencing the experimental phenomena (that is, visually, analytically, and tactually) alongside the display, (c) by providing fast feedback that allowed students to associate the graph immediately with the event; and (d) by the generally high motivation associated with the MBL experience (Barclay, 1986; Brasell, 1987; Linn et al., 1987; Mokros & Tinker, 1987). The first three aspects, and maybe the fourth also, facilitate student understanding mediated by the display.

2. It has been proposed that the real time display provided memory support, placing less overload on working memory, thus facilitating the transfer of the event-graph unit into long-term memory as a single entity (Beichner, 1990; Linn et al., 1987; Linn & Songer, 1991b). "The computer seems to be functioning as an auxiliary memory" (Nakhleh & Krajcik, 1991, p. 24), leaving students to focus on what was happening, and why it was happening.

3. Social construction of knowledge was seen to play an important role in the MBL, and this seemed to be more pronounced with adolescent participants as compared to younger children (Linn & Songer, 1991a).

4. The MBL plays a role in changing the nature of student experiences, as compared with traditional laboratory experiences: "MBL does not necessarily teach students how to think so much as it frees students to think about what their experiments mean." (Nakhleh, 1994, p. 377; see also Rogers & Wild, 1994)

5. Students may evaluate computer-generated graphs uncritically, much as they assess textbook presented graphs (Nachmias & Linn, 1987): "These studies suggest the value of more detailed analysis of individual students as they perform laboratory experiments" (p. 504), to determine how different students make assessments and select the ideas they retain, and to understand better the conditions that support conceptual change.

The ensuing analysis of student discourse follows this latter advice, and examines four aspects of the processes by which the display mediates students' understandings. They are: (a) how students critically evaluated (or failed to evaluate) the display graphs, (b) how they collaborated in building mental constructs, (c) the role of the teacher's interactions with dyads, and (d) student limitations and delimitations in learning about thermal physics in the MBL.

4.4.1 Students' assessment of graphic data

In section 4.2 it was shown that students viewed the display, predominantly, as synonymous with the experiment phenomena. From another perspective, the question is now asked, "Did the students view and accept the displayed graphs uncritically?" Alternatively, did students evaluate graphs for their degree of consistency with their subject matter knowledge? Were irregularities in graphs due to various errors judged to be within acceptable ranges? Were the graphs judged to be suitable and sufficient representations of their experiments for further interpretation?

To answer these questions, the transcriptions of audio recordings of three dyads, annotated with students' gestures, expressions and actions taken from the video recordings, were used as principal data sources. As the students worked through each POE task, the analysis began at the start of data logging when the graph began to take shape, and continued through to the end of their analysis of the particular graph.

4.4.1.1 Analysis

With each experiment the students were faced with a decision to accept or reject the graph on two grounds: the suitability of their time and temperature range selections, and whether they could reconcile the graphic feedback with their expectations for the experiment. Alternatively, they could have viewed and accepted the graphs uncritically.

In the first instance, students sometimes underestimated the duration of an experiment. On an occasion when Dyad A found their graph had finished before it reached a maximum, Ivan asked "You reckon we should do it again for longer, so we can get a time constant?" (line 112). As the graph had taken only five minutes they decided to repeat it. When Dyad C realised too late that they had allowed only 10 minutes on their time axis for a 25-minute cooling graph, they used their initiative and after 10 minutes simply repeated the graph, overlaying the second on the first, as shown in Figure 4.5.

The end result allowed them to compare the cooling rates of two materials effectively without having to restart the experiment. Frequently, as soon as the salient features of a graph became evident and sufficient, students stopped the graph early to conserve time.

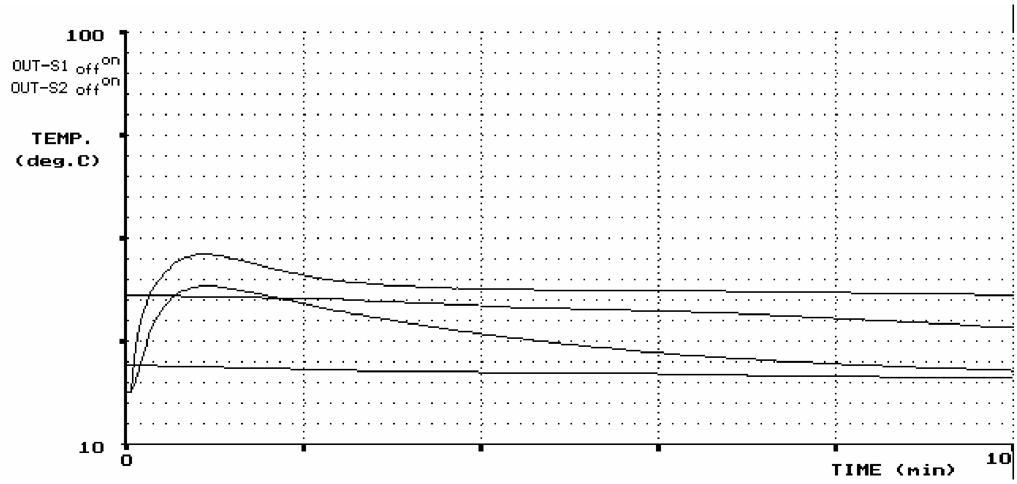


Figure 4.5. Students overlaid graphs to save time, rather than repeat an experiment.

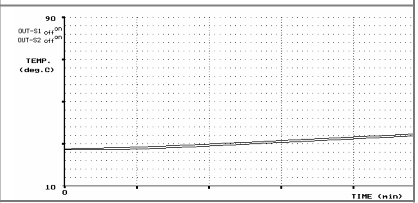
To select temperature ranges, dyads either used the values recommended in the POE notes, or displayed digital values of the sensors on the screen to obtain an indication of a suitable starting temperature. Dyad A became concerned with the range selection for their first task, as the graph line rose quickly towards their set screen limit of 80 degrees

42	Ivan	Ready. (He starts the graph and both look at the screen, then make weird noises.) 42 43 44 45 [degrees]. Oh no . . you reckon we should re-do it? It's going to get to 100 [degrees] easy.
43	Mike	It won't.
44	Ivan	Yeah it will.
45	Mike	It won't. It's going to stay at 99 or so degrees.
46	Ivan	Why's that? (Ivan turns from screen to Mike.)
47	Mike	So that it doesn't boil . . . in any case we need to do this . . . .

Ivan's concern that the rising temperature might exceed 100 degrees was dismissed by Mike (line 45), who explained that the upper limit would be the boiling point of water. Mike's quick assessment of the graph combined his knowledge of physics with confidence in the sensor data.

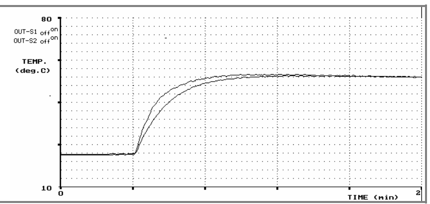
Curiously, on the third day, a similar situation arose again. Mike and Ivan were measuring the temperature of metal immersed in boiling water. When the sensor reading reached 107 degrees, neither voiced an objection. (The sensor had been calibrated wrongly.) Their reason for not querying the impossibility of the 107-degree value was not pursued in later interviews. However, a possible explanation may be conjectured. During this experiment Mike and Ivan had grappled with the relationship between two graphs, made difficult due to poor data resulting from inadequate experimental techniques. According to the mental models theory of Johnson-Laird and Byrne (Barrouillet & Lecas, 1999; Johnson-Laird & Byrne, 1991), students construct mental models or imaginary sketches of the possibilities of a situation and work from these. These mental models are kept in working memory, the short-term memory that supports reasoning. Working memory runs out of space very quickly, and when confronted with a lot of options a discrepant event (in this case the 107 degree temperature) becomes the first casualty of a "full memory." It appears that Ivan maintained in his mental models an imaginary sketch of metal-in-boiling-water at 100 degrees, and the vital information of the 107-degree temperature was left off his "drawings." The low capacity, short-term memory that supports reasoning runs out of space very quickly (Brooks, 2000). As for Michael, he paid only peripheral attention to Ivan's measurement, being engaged at the time in writing, which may explain his failure to query the measurement error. Whatever the explanation, this instance arose in connection with a digital screen display, rather than a graphic display and their critical assessments of graphs.

Students expressly made allowances for minor irregularities in graph shapes, and correctly attributed these to experimental errors and sensor limitations. David and John were heating two sensors under as-near-as-possible identical conditions. The two graph lines diverged ever so slightly, which led to this exchange:

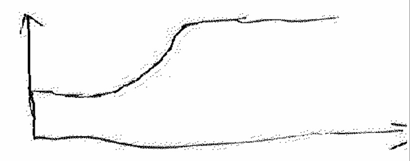
1052	John	The first one's getting up further [i.e., Sensor 1 higher than Sensor 2].	
1053	David	That's right because that one was 0.1 degrees ahead to start with, the margin of error to start . . . Yes the error's up to 0.2 because that's the margin of error that sensors have.	

Graphing errors within the limits of sensor variations were judged as acceptable (line 1053).

There were occasions when students accepted a graph that did not conform to the predicted shape. Mark had placed two sensors in hot water and measured the times until the sensors reached their maximum temperatures.

57	Mark	Yeah, but . . . How long did that take? About 40 seconds to get an answer?	

Mark made no immediate remark about the shape of the curve. But when it came to writing down observations and explanations, he said:

76	Mark	I thought it was going to go up (finger tracing his POE prediction shown at the right) like . . like that.	

After some discussion with Shaun, Mark went on to read his explanation of the shape of the display graph.

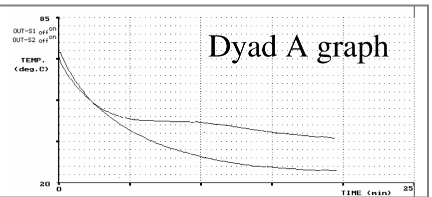
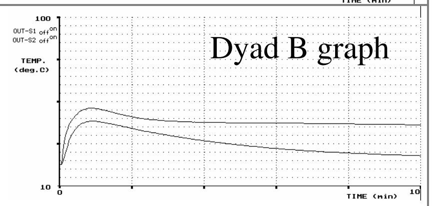
94	Mark	(Reading the finished Explanation section of his POE notes) "The curve of graph was more convex that it was concave, because the sensors were placed in a sudden change of temperature, instead of being gradually warmed up." (Both continue to write.)

Should it be concluded that Mark assessed the original graph uncritically since the graph was certainly not what he expected? To the contrary, Mark accepted the graph on the basis that he could construct a rational explanation for its inverted shape. Mark was asked in a later interview "Why do you take (the graphs) as being accurate?" He replied "Because it [the computer mechanism] is pretty fine tuned. The equipment sort of takes readings – time readings – every couple of milliseconds or something, I suppose . . . within 0.1 degrees." (AS2071099) Mark had a basis for expressing confidence in the accuracy of the display, and from this viewpoint it might be said that as the graphs grew dynamically he had reason to assess them, critically, as being reliable. While Mark and Shaun were not videorecorded after the first session, all of their later graphs were successful experimentally, so there was no occasion when they were called upon to assess critically a graph that was patently in error.

Major irregularities did appear in some graphs by Dyads A and C, due to their poor experimental techniques, and they did not accept these graphs but repeated the experiments.

Uncertainty with a display frequently led students to visit other groups and ask about experimental techniques, graph parameters, the number of sensors used, and starting temperatures. Particularly when a graph held some difficult-to-explain feature did one or both students visit another dyad to crosscheck results. When the visiting students drew comparisons between graphs, they were able to distinguish between inconsequential factors such as differences in temperature ranges or time scales, and comparative aspects of graphs that were important. For example, Dyad A found the temperature of 100 ml of water rose 7 degrees after 100 g of hot iron was dropped into it. They wanted to know what temperature rise Dyad C found for the same experiment. The comparison revealed that Dyad A had not recorded accurately the initial temperature of their water, and this affected their measurement of the rise in temperature. Consequently Dyad A improved their experimental techniques.

Again, when Ivan and Mike were puzzling over the horizontal section of their latent heat graph, Ivan conjectured that the initial temperature of the liquid might have affected the shape of the curve. So he made a brief visit to Dyad B in the adjoining room, and returned to Mike with this report:

498	Ivan	Because on their graphs it started a bit lower (touching the screen, then going into the other room to find out the starting temperature of the Dyad B graph).	
509	Ivan	(He has just returned.) They have all started about the same temperature as we have. They used kind of a small temperature change but we were exactly 5 degrees per band but out there they're not. Their bands [vertical temperature divisions] were differently spaced, so that was the big difference.	

It is not clear how Ivan claimed other dyads started their graphs at the same temperature, however he concluded correctly that the graphs were fundamentally the same, only differing in scaling factors. Consequently he and Mike looked for an alternative explanation for the horizontal section of their graph.

Inter-dyad exchanges were common to all groups in the class, as attested to by the teacher's journal notes and interviews with students. These exchanges seemed to reassure students at a number of levels: that their basic procedures and techniques were being conducted correctly; their graph shape was consistent with those from other groups; and they were fundamentally proceeding in the right direction. Rather than question the reliability of the computer-generated graphs, dyads sought to confirm that they had created the graphs using valid experimental techniques.

4.4.1.2 Discussion

<u>Assertion T5.</u> Students critically evaluated the appearance of the graphic display.

The creation and interpretation of graphs as models of physical phenomena are central to physics laboratory activities. While the student participants had extensive experience with kinematics graphs, this was their first encounter with thermal graphs. As illustrated in the analysis, all videotaped dyads evaluated their graphs critically based on a number of criteria. Firstly, they adjudged the suitability of the time and temperature scales, and where necessary re-started experiments with new parameters. Secondly, the finished graph had to contain all the data necessary to support explanations and calculations. Thirdly, the information conveyed by the graph had to be consistent with the students' background knowledge. Fourthly, minor human and electronic errors were allowed for in accepting less-than-perfect graphs. In view of how students applied these criteria, there was no consistent evidence that students tended to evaluate computer-presented graphs uncritically. Interviews also revealed that students' confidence in the reliability of the display was grounded in the hardware and software technology.

The study by Nachmias and Linn (1987) investigated students' critical assessment of graphs generated by computers, in the light of their knowledge of (a) the subject matter, and (b) the restrictions of the software and hardware used. Students inexperienced with temperature graphs tended to evaluate the graphs uncritically, failing to identify errors caused by false hardware and software settings. They tended "to evaluate computer-presented graphs uncritically much as they assess textbook-presented graphs and other scientific information" (1987, p. 502). MBL equipment has advanced over the past decade and graphs are not effectively constrained by the (poor) precision of the hardware or software. While the students in the present study were also inexperienced with thermal graphs, they had an ability level higher than the average for students of their age. Further, they were three years older than the children in the study by Nachmias and Linn.

4.4.2 Dyadic discourse and graph interpretation

This section of the analysis touches on the most interesting aspect of student activities in the MBL. It examines how students collaborated in building mental constructs: the range of techniques and activities they devised; instances of constructing new concepts; how the display served as a referent source of information; and, how they drew on prior knowledge and resources.

The principal data sources were the transcripts of the audio recordings annotated with students' actions taken from the videotapes. These were supplemented with student POE notes and the teacher's journal of classroom observations. The unit for analysis ranged from one to multiple turns of speech, which completed an action, led to a conclusion, resulted in a calculation, or was an isolated question-answer exchange. The dialogue included discussions before, during and after experiments, but (with one exception below) excluded passages in which the teacher participated. Excerpts from three experiments conducted by Dyads B and C were analysed.

4.4.2.1 Analysis

On the first day Mark and Shaun were discussing how the temperature readings of the sensor would be affected by its degree of thermal contact with hot objects. Their task read:

> If the temperature sensor is placed inside a narrow test tube then placed in hot water, how will this affect its operation? Can you mention thermal contact in your discussion? Estimate the time constant under this condition.

Both examined the equipment, and then discussed their understanding of the terminology.

142	Shaun	(After both read the task Shaun reads aloud from the worksheet.) "Can we mention thermal contact in the discussion?"
143	Mark	Thermal contact. NO. . . No we can't.
144	Shaun	Why not?
145	Mark	Thermal contact's physical contact.
146	Shaun	Yeah, but the water's touching the glass, the glass is touching air, the air's touching the sensor.
147	Mark	Yeah but the sensor's not touching the water (Shaun: = No) so it's not thermal contact.
148	Shaun	At least it'll get hot.

Initially Mark stated emphatically that the sensor in the test tube had no thermal contact with the water. Shaun reasoned by inference (line 148) that, insofar as the sensor would heat up inside the test tube, it must be in thermal contact with the hot water. Mark accepted this reasoning and wrote later in his POE prediction: "It will take longer because the heat is not as direct (thermal contact)."

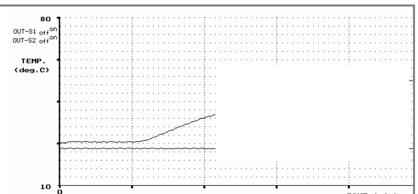
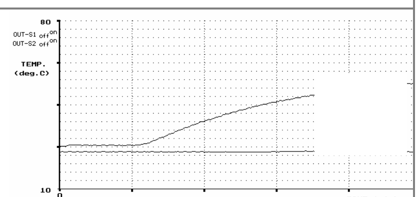
For the previous experiment the sensor was placed directly into hot water and the temperature curve rose quickly in a convex curve. Now they faced a task with the sensor first enclosed in a test tube and then placed in hot water.

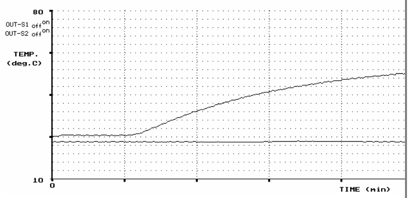
154	Shaun	Alright, how do you predict what will happen? . . . I reckon that the temperature will rise really slowly – but not really slowly, it will have a slight curve . .
155	Mark	No on the bottom it'll be flat.

156	Shaun	It'll be linear (his hand rises along shallow slope) – like a straight line that's curved (his hand sweeps upwards).
157	Mark	A straight line . . oh . . yeah.
158	Shaun	Like a constant acceleration (gesturing a gentle slope upwards).
159	Mark	Yeah.
160	Shaun	(He points to the blank graph display on screen) Like – what's that – how many seconds is that (counting divisions along time axis with finger)? Five. . . I'd say about a minute or a minute thirty to get to the top temperature . . . surely it's got a highest temperature. [Shaun apparently makes a comparison with the previous curve, and estimates the time it will take to reach its peak.]
161	Mark	I'm going to say . . I'm going to say . . and ah . . I'm going to say what I said last time, that it's going to . . (Shaun: = Yeah) curve up . . slowly. Right?
162	Shaun	(Both are writing their predictions.) I think the graph will be a linear graph . . . slope . . . the slope won't be very steep.
163	Mark	(Reading aloud as he writes) "It will take longer because the heat is not as direct . ."
164	Shaun	(Looking to Mark) as thermal . . thermal contact . . (??) thermal contact with water.

Both students predicted the new graph shape based on their previous graph. Shaun demonstrated with his hand (line 156), and imagined superimposing his mental image of the graph on the blank screen and estimated how quickly it would reach a maximum (line 160). He drew a comparison with a similar curve from his MBL motion experiments seven months earlier: "Like a constant acceleration (gestures gentle slope upwards)" (line 158).

After the experiment began both students examined the graph's growth. Shaun boasted at his predictive prowess (line 188, 190), to Mark's mock chagrin (lines 189, 191).

188	Shaun	I'm pretty good at predicting this stuff.	
189	Mark	So far it's a straight line.	
190	Shaun	YES . . . a straight line . . yes! I'm a genius.	
191	Mark	You make me sick (some banter passes between them). (Both watch as graph passes half way.) . . . Hey what is this ah sort of starting to ah take the same track as the one we had before . .	
192	Shaun	Yeah well not really.	
193	Mark	It is (touching the screen) . . it's still. .	

194	Shaun	Yeah I suppose it's . . hey look it's still going up . . (They look at the screen and talk idly for 20 seconds while they wait for the graph to finish.) . . . (?) good gracious so it really does [i.e., tend to level out]. (Shaun leaves the room.)	
195	Mark	(He talks to himself and write notes.) OK, what have we got . . a graph . . It almost looks like the top of someone's head and very very flat. It's much the same effect as we had the first time. (The teacher enters with Shaun.)	

Shaun was surprised (end of line 194) that the graph started to level out, instead of rising in a concave curve, and he left the room. After returning with the teacher, both students went on to explain their results quite lucidly. Each checked the other's notes as they crystallised their explanations in the written POE notes. Speaking together, reading their POE notes aloud, inquiring of the teacher about procedures, explaining results to the teacher, and comparing graphs with those of other dyads were regular features of group activities.

The next task asked:

> If the sensor <u>touches</u> a hot object, such as one of the solid metal cylinders pre-heated in hot water, how quickly will it measure temperature?

Mark and Shaun compared their predictions, which differed slightly.

271	Mark	What'd you write?
272	Shaun	"The graph will rise quickly like Task 1."
273	Mark	I don't really know.
274	Shaun	Yes I think it will.
275	Mark	I mean. .
276	Shaun	It'll probably get pretty hot.
277	Mark	I think that it will rise really quickly for a short period of time then it'll . . ah . . slack off . . (Mark writes his prediction; the teacher enters the room.)

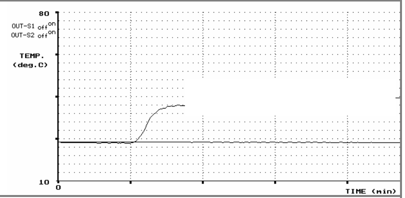
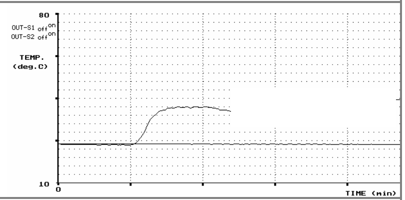
The next time the teacher entered the room Shaun raised the issue of their differences.

284	Shaun	We don't have to have the same predictions do we?
285	Teacher	Well no.
286	Mark	No because nobody has the same ideas and peer conflict and stuff like that.
287	Teacher	You – you might want to discuss it. You mightn't agree . . On the other hand . .
288	Shaun	Well we've both had different predictions, and one's been right and one's been wrong (Teacher: = Yes) then we've both been wrong.

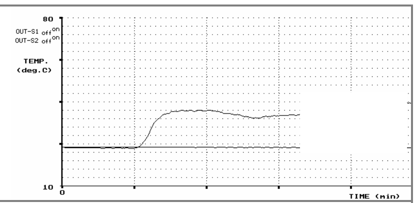
289	Mark	Yes (= the second one) [i.e., Task 1.2]
290	Shaun	(= Yes.) And we see that one is like more right than the other (Teacher: = Yes).

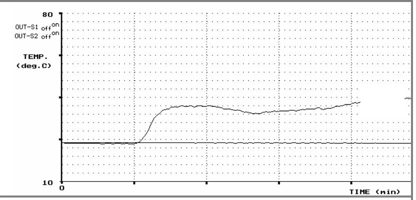
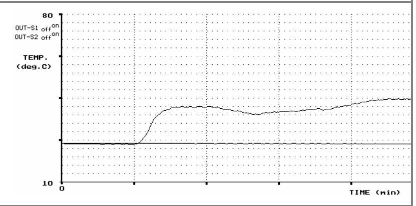
Shaun sought reassurance that each was free to express a conflicting opinion, while at the same time both acknowledged that they had predicted wrongly to varying degrees. The interchange suggests that as they went about their tasks, they were aware that their collaboration was not restricted by internal or external expectations of procedures or results.

Once the experiment began, as cited below, both found graphic evidence confirming their POE predictions (lines 296, 299 and 301).

296	Shaun	(He places one sensor against the hot metal block, the second sensor held in the air nearby. They watch one graph line rise, the other stay at room temperature) . . . I'm a genius.	
297	Mark	What'd you say?	
298	Shaun	Oh hang on (adjusting the second sensor in the air close to the block) . . .	
299	Mark	Don't put it too close. . . . Nah, see (pointing to the graph levelling out), I'm right I'm right . .	
300	Shaun	What did you have?	
301	Mark	AH! See (pointing to his notes)! (Reading) "The graph will rise quickly for a SHORT period of time" (touching his POE notes with one finger, the other finger touching the graph line on the screen) – about 20 seconds – "before levelling out" (touching the level section on the screen).	

Then in line 303 Mark concluded from the graph that Shaun was not holding the sensor close against the hot metal.

302	Shaun	Now it's going back down again (as if to challenge Mark's prediction).	
303	Mark	You're taking it off . . well don't take it off.	

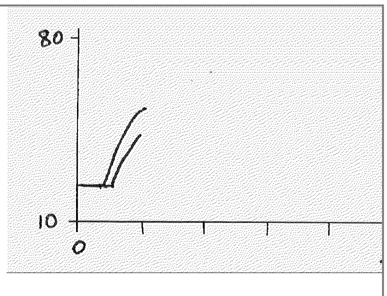
304	Shaun	I’ve still got it on and it’s going down.	
305	Mark	Is it on on (checking closely how Shaun is holding the sensor next to the block of metal).	
306	Shaun	Yes it’s on on (his eyes fixed on the screen). It’s on hey! (He stops Mark from moving the sensor.) . . It was ON. Hey it’s getting hotter again.	
307	Mark	Yeah (both watch screen) . . . (?) secondary (?) and secondary heat. (They watch the graph continue to the finish.) . . . any time now (and the graph finishes) . . . you’re starting to annoy me . . I can’t handle it.	

Looking at the screen, Shaun (line 306) reassured Mark, as he adjusted the experimental apparatus to obtain feedback through the display. The good-natured banter (line 307) about their predictive abilities continued through each lesson, reflecting the cooperative rather than competitive spirit which prevailed throughout the class over the four days.

Their collaboration extended to scaffolding their understanding of new terms, interpretation of tasks, and the interpretation of observations. For their first experiment, discussed earlier in a different context, Mark and Shaun addressed the question:

> Does a thermometer or temperature sensor, initially at ambient temperature, give an <u>instant</u> reading when placed, say, in hot water?

They prepared the sensor and a beaker of hot water.

18	Mark	Now stick it in. Stick both in. (Shaun puts one sensor in a beaker of hot water for 7 seconds; Mark picks up the second sensor and puts it in for 5 seconds. Both look at the screen.) So it does. (Mark then removes Sensor 2, and Shaun removes Sensor 1) [“So it does” refers to the question “Does the sensor give an instant reading?”].	
19	Shaun	Yup.	
20	Mark	Press F1 to stop?	
21	Shaun	Yup. So we write “Yes.” (Shaun starts to write at top of notes then hesitates.) . . . Hang on hang on (looking closer at the task question).	
22	Mark	(Looking across to Shaun) We’re supposed to write that here – “Predicts.”	

23	Shaun	No but that has to (??). (Shaun shakes his head, indicating the way they went about the task was wrong. He leans close to Mark and points with his pen to the question and directions in the box.) "Does a thermometer . . . instant reading when place in hot water." So it's NO, it doesn't give an instant reading of temperature of 80 degrees or whatever that is (touching the beaker of hot water).	
24	Mark	Yeah.	
25	Shaun	That says "No," that's the answer to that question.	

Mark's claim (line 18) "So it does," in answer to the question "Does it give an instant reading?" was made on the basis that the graph began to rise immediately the sensor was immersed. Shaun initially agreed (line 21), then hesitated, and would not be rushed by Mark (line 22). After reading the task more carefully, Shaun (line 23) explained to Mark that the sensor did not read the maximum temperature instantly. Mark accepted his interpretation of the task. He now understood that the important feature of the graph was not the initial slope, but how long it took to reach its maximum value. This understanding also made it possible for them to answer the next question about the time constant for the sensor.

As with Dyad B, David and John in Dyad C began most tasks by discussing extensively their understanding of the factors influencing the predictions. Task 3 required they determine which of four metals would be best suited to make a saucepan. In the following dialogue both based their selections very much on guesswork. David initiated many of the factors to consider, and John responded. David suggested the best metal would be stainless steel. However, John's choice of copper started David speculating about the use of copper in pipes, and the "low conductivity" of copper (line 435).

431	David	. . .So I think stainless steel will be the best one won't it?
432	John	I reckon copper (as he examines a copper rod).
433	David	Ah if you hold them . . yeah cause . . well that's what they use in pipes isn't it.
434	John	We won't be able to say for sure.
435	David	No. . . . You know how the old copper pipes (John: = Yeah) . . . . I don't know (examining a rod) . . . does that mean they use copper pipes because its got low conductivity, or . . . I don't know, it's just a guess (John: = Yep) . . . (He reads the POE Task) "What temperature-time graphs do you expect?" . . .
436	John	I guess we just draw them . . . Draw one for copper which goes (drawing a convex upwards curve on the bench with his finger) . . steeply . . iron and steel and . .

437	David	Well hold on no won't . . the best material will be the one that increases the least in temperature . . . won't it? . . . . no hold on.
438	John	These are saucepans . .
439	David	Yeah but are they talking about the handle or the actual . . .
440	John	The actual saucepans.
441	David	Alright what's the actual saucepan then you want.
442	John	It heats up (David: = Yeah) fast – real fast.
443	David	Yeah. (They both start to draw graphs for their predictions.)

David hesitated (line 437) when he saw John draw a steep temperature graph on the bench, and suggested the ideal metal should heat slowly if used for the saucepan handle (line 439). John disagreed, repeating (lines 440, 442) that the saucepan itself needed to heat up "real fast" (line 442).

As they drew their prediction graphs David mentioned the "heaviness" of iron, the "lowness" of aluminium and non-rusting of stainless steel (lines 445, 447 and 449).

444	John	Fe Iron (drawing this graph first) . .
445	David	Yeah but ah iron's also really heavy . . .
446	John	Aluminium (?) . . the temperature (?)
447	David	Aluminium would be pretty . . pretty low . . (Both draw graph lines.)
448	John	Now steel . . mmm . .
449	David	Stainless steel is most commonly used, but that's because it doesn't rust . . . . I reckon iron next, then copper, and then stainless.

This shared background knowledge continued to feature in their dialogue as they conducted the experiment. They did this by attaching sensors at the top ends of aluminium and copper rods, stood the rods in a hot water bath, and graphed the temperature rises as heat was conducted up the rods. They repeated the experiment with the other metals. Though both predicted stainless steel would be the best conductor, they were surprised to find it conducted worst of all. Their graphs also showed, due to an experimental error, that aluminium conducted slightly better than copper.

Fifteen minutes after completing this experiment, and while waiting for the lengthy Task 5 graph to finish, John and David turned their notes back to complete the "saucepan metal" explanations. By this time the teacher had directed their attention the Table of Thermal Conductivities in the POE notes. Based on this table they realised their results for aluminium and copper were reversed; also, that both conducted heat much better than iron or stainless steel. In the following extract, David suggested both metals were "less dense" (line 669) and have high heat and electrical conductivity. He also conjectured that heat travelled faster through a less dense metal (line 671), and wrote his POE explanation accordingly.

669	David	Yep, OK . . Why did aluminium rise highest but it was really copper . . OK so they're both . . umm less dense. . (??) (John: =Yes) and they both have high heat and electrical conduct – well copper's got electrical conductivity as well as . . [Note: Copper is not less dense; also this is the first time electrical conductivity has been mentioned].
670	John	Yeah . . aluminium . . . anyway
671	David	OK but yeah. If there was a small level of water in the bottom the heat would travel FASTER up it because it's a
672	John	less dense metal . . yeah.
673	David	Alright. That's enough for an explanation (writing POE notes). (John has examined the rods carefully during the last few turns of talk; then starts to write. He again picks up copper and aluminium and compares them with iron. David also tries to 'weigh' them in his hand.) You know copper's heavier than iron – John (to get his attention).
674	John	(He 'weighs' both also) Yeah. (They look at each other.)
675	David	But see that bit is right, because that's what the electrical conductivity constant is as well. On Question 6 for homework (turning to p.8 of his notes) . . ah . . copper and aluminium are the most conductive . . in fact copper is the second heaviest metal and yet it's also the most conductive. . . [Note: John scratches out his POE comment that Al and Cu are less dense than the other metals].

While David wrote (line 673), John silently compared the weights of the aluminium and copper rods in his hands. David tried the same (line 673), and realised that his density theory could not apply to copper. While David forgot to correct his POE notes, John crossed out his unfinished explanation based on this concept. David drew support for his conclusion based on the Table of Thermal Conductivities (which he erroneously referred to as "electrical" conductivity in line 675).

Five minutes later the students returned to this task to recommend which of the four metals was most suitable for use as a saucepan. David's recommendation considered the chemical and physiological effects of copper.

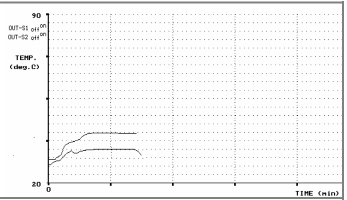
712	David	I've put down aluminium (writing) . . . cause it doesn't TASTE terrible. . . . "Aluminium" – I don't know – "it conducts almost as well as copper, and it's less hazardous."
. . . .		
714	David	Yep because if a copper saucepan is left to set for a long time they can start to oxidise kind of . . what would you get . . a small amount of copper oxide on the surface? Which is certainly not good if you are cooking . . .

The students finalised this task almost one hour after they began it, and completed two other experiments in the interim. This analysis of their Task 3 illustrates how David and John drew on general knowledge, chemistry, textbook tables and incidental observations, resolved differing opinions, used the POE task questions to clarify their thinking, and undertook multiple experimental activities in parallel.

On Day 3 David and John began Task 7:

> Given chunks of two different materials, each of the same mass, would you expect that different materials contain the same heat energy if they are at the same temperature?

After a lengthy discussion they began the experiment, dropping a hot slug of copper into a calorimeter and watched the temperature graph rise, and repeated this with an aluminium slug. To compare the graphs (line 910), David referred to the Table of Specific Heats.

910	David	OK . . . (both write, copying the graph). Actually, I think that works in perfectly with our results (turning to p.16 specific heat data) because . . hold on.	
911	John	(Head buried in writing) Not really . . you don't know . . (looking up at David) you can't really predict. (He looks tired.)	
912	David	Yeah but	
913	John	which element's gonna . . and by (David: = I mean) (= how much).	
914	David	Yeah you can't predict how much but	
915	John	unless you are an Albert Einstein.	
916	David	It'd be interesting to try if we had a 50g piece of stone because if stone was like 40 – 40.6 or so then we would know our results were pretty much spot on, because all the others are all proportional (as he gestures by hand a series of levels).	

David made excellent use of the specific heat data and proposed an experiment (line 916) to test his hypothesis.

Student dialogue also revealed a number of alternative conceptions, otherwise described as intuitive conceptions (Linn & Songer, 1991a). Many students expressed the thought that some materials had a better ability to "retain heat" than others. In this experiment John partially filled a beaker with hot water and inserted two metal rods to compare their thermal conductivities.

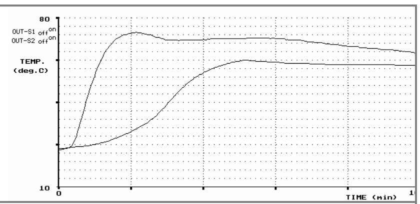
486	John	Some heat's been going into the beaker as well.

487	David	Yeah, well it won't retain the heat. Probably because it is not as dense as aluminium.

David did not enlarge on this ability of the denser material to "retain the heat" better (line 487).

In another experiment in which test tubes holding 2 cm and 1 cm of hot water were cooled, David remarked "the 2 cm should retain the heat longer than the 1 cm, shouldn't it?" (line 603), to which John agreed. David wrote "the larger body of water retains the heat for longer" (POE notes p. 9). In this case the teacher could assume that David correctly associated "retaining heat" with internal thermal energy. However, this was not the case. He was speaking about "maintaining its temperature longer." During the first two days each of the six students videotaped associated the phrase "retaining heat" with a slow cooling curve, as evidenced in their dialogue, POE notes, and interviews. In this sense they equated heat with temperature. They had not yet conceptualised the differences between heat and temperature, nor been introduced to the concept of heat capacity.

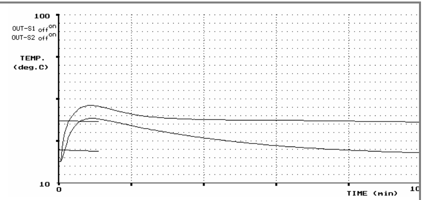
This led students to draw other alternative conceptions. For example, in an interview (AS2071099) after Day 1, Mark and Shaun were asked to comment on the saucepan experiment. The upper line on their graph below showed the rate of heat conduction through a copper rod, and the lower line through stainless steel.

Teacher	So what's the difference between stainless steel and copper? [Though their graph appears on the right, they were asked to comment on this from memory.]	
Shaun	I reckon that the stainless steel one, it rose up slower, but it held its heat for a while longer.	
Mark	It would probably be better for an oven.	
Teacher	Why do you say for an oven?	
Mark	Cause after you turn it off the heat will sort of stay in there.	

Shaun explained that the stainless steel "held its heat for a while longer," insofar as its temperature decreased more slowly, as seen in the right half of the graph lines. (The students had not been introduced to factors such as heat capacity or Newton's law of cooling that are relevant to an accepted scientific explanation of the cooling sections of the curves above.) Consequently Mark concluded that stainless steel would make a good oven because it would keep the heat inside.

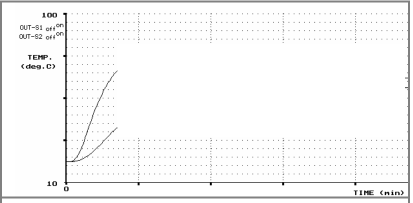
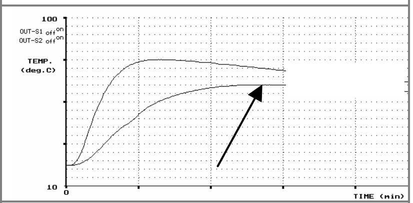
The tasks in the POE notes were scaffolded, and on Day 3 the first task was to investigate the difference between heat and temperature. The second and third tasks introduced the concepts of heat capacity and specific heat. David now changed to a more canonical explanation for the slow cooling curve for water: "The water will cool slower *as it has more heat energy that must be lost* [italics added]" (POE notes p. 15). None of the students continued to use the phrase "retaining heat" after Day 3, and couched explanations in terms of heat capacity and specific heat.

The analysis of dialogue revealed the capacity of students to construct plausible explanations. For Task 5 two test tubes containing hot lauric acid and pentanol were suspended in air, and sensors inserted in the liquids. As they cooled, only the lauric acid solidified. A widely held explanation of the latent heat cooling curve for lauric acid is illustrated by David's comments below. In the graph shown, the upper line is the cooling curve for lauric acid, which becomes horizontal as it solidifies. The lower curve is for cooling pentanol.

731	David	Yeah . . It doesn't make sense [i.e., the flat lauric acid cooling curve] (as he views the screen and thinks) . . . Maybe the heat's trapped . . . because there's nothing – see there – if it solidifies on the surface first (touching the outside of the lauric acid test tube) it means that to escape the heat has to pass through a solid layer . . whereas here (touching the pentanol test tube) the heat can just (opening his hand upwards over the test tube) evaporate up through the air . . .	

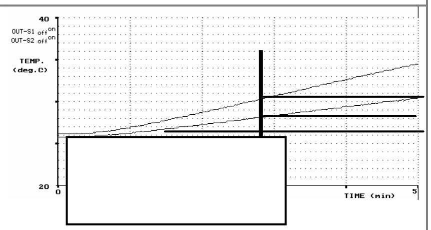
David's explanation for the constant temperature of lauric acid during change of state was that, as the acid solidified against the test tube glass, it acted as an insulator thus preventing heat from escaping. This explanation was sufficient and complete from the students' view, especially as it was consistent with what they could see and feel with the test tubes. (Following a subsequent theory lesson about latent heat, one student wrote an addendum to her POE note: "It was only after class discussion that I understood this," that is, the scientifically accepted explanation for the flat part of the curve.)

The analysis also identified a broad range of conceptual models and similes used by students. During Task 3 Mike and Ivan heated rods of copper and iron, and viewed the temperature graph as it developed. Between them, in the one task, they made use of six different conceptual models to interpret the results.

285	Mike	That would be the copper (as both Mike and Teacher touch the steeper graph on screen) you can actually touch that and feel that . . . it's . . . quite hot (touching the top of the copper rod).	
305	Ivan	It comes down to the molecular level . . (Teacher: = What's that?) Does it come down to the molecular level? The atoms inside?	
306	Mike	(??) there is actually a constant (turning to his Day 1 homework, with the table of thermal conductivities he could not find earlier in the lesson) . . . assigned to each metal . . . thermal conductivity.	
320	Mike	You could draw how quickly it reaches its max temperature . . because (touching the screen) iron has kind of dropped down there . . . it's not going any higher than it is. . .	
328	Mike	(He looks at his notes reflectively.) You could also look at the time constant which is probably a more accurate way of . . .	

Mike (line 285) (a) views the graph image and (b) feels the copper rod; Ivan (line 305) brings to mind (c) the molecular and atomic levels; Mike (line 306) refers to (d) a table of thermal conductivity, and (line320) (e) a mathematical model; and finally Mike (line328) refers to (f) the time constant concept. Students used three different tables of data, and in connection with the concept of heat energy content they implicated mass, volume, surface area, density, liquid versus solid states, lattice vibrational energy, atomic size and packing, and various mathematical formulae. Graph curves were likened to the shape of a bowl, the profile of a man's head, "a constant acceleration" graph, and traced on the bench and in the air. On a few occasions Mike and Ivan turned off the monitor displaying the developing graph, in order to envisage mentally the shape of graph to come. They turned the display on to check their predictions.

The analysis has previously given attention to the role of the display as a resource around which students developed their dialogue. This was particularly the case during a number of sequences in which students used the screen as a working diagram for mathematical analysis. In the following extract Mike and Ivan had just heated two 100 g blocks of aluminium and iron with 1-watt heaters for five minutes and graphed their temperatures. Together they theorised that the vertical rises of the two temperature graphs would be in the ratio of the specific heats of iron and aluminium (line 994).

994	Mike	(Speaking loudly to Ivan) Iron and aluminium. . 's about half. [Specific heat of iron 470 J/kg/^{o}C, and specific heat of aluminium 910 J/kg/^{o}C.]	
996	Mike	Yep. The specific heat (pointing to the graphs) and that's pretty much conclusive (holding a sheet of paper against the graphs as shown) with the results we've got there . . .	
1002	Mike	Yeah well we've basically got the specific heat part of it.	

Mike then held a sheet of paper vertically against the screen, and estimated that the rises were in the ratio of 1:2 (roughly the ratio of the specific heats), which verified their prediction.

On numerous occasions students measured the screen directly to calculate derived quantities. When David and Shaun took screen measurements and related their calculations to the standard formula $Q = mC(t_2 - t_1)$ they were quite elated as they spoke to the assistant to the researcher.

1174	David	Pretty good. (The assistant enters.) WE actually managed to PROVE something. [David uses "prove" to mean "verify"]
1175	Assistant	And what was that?
1176	David	We just . . on this one here [Task 10] we were trying to prove the specific heat constant (referring to the Specific Heat Table) and iron heated up about twice as much as aluminium (pointing to the graphs).

The question as to whether the screen display served as a memory aid arose from the literature. From the transcripts of ten interviews, and the ten completed questionnaires, the majority of students replied they were able to recall mental images of specific graphs for some time after the experiment. "To me it is [a memory aid], because I am a visual person, like if I see something it's quite easy for me to remember it rather than if I hear it" (Tina, AS1121099).

Students said extended viewing of the graph image helped them evaluate results during and after experiments.

> It was easy to explain things because we had a graph sitting in front of us. You could directly relate to the graph. We could look at the graph and say: This point here is the maximum point, where it had reached the ambient temperature, or whatever had been going on in the experiment. It was a lot easier to explain. (David, AS2081099)

> Yeah I think I agree. When cooling the [lauric] acid it was, when it solidified again. We could see it [the lauric acid], as well as see the graph, so we could pinpoint almost exactly . . . (John, AS2081099)

Some spent up to fifteen minutes discussing and measuring features of a single graph. From the teacher's perspective, the original display (rather than an inaccurate copy in notebooks) proved invaluable for students' detailed analysis. Further, students were relieved from "the times for the readings of the thermometers and things like that" (Shaun, AS2071099), "and your ability to draw a graph – it would have been painstakingly slow" (Mike, AS2071099), thus freeing the students to concentrate on formulating their ideas. During a lengthy experiment Shaun said "you could actually see it, the graph, and you could just imagine it a bit more, how the temperature was going, and how the object was heating up" (AS2071099).

The relevance of the social context of student activities in the laboratory also arose from the literature. A reading of interviews, questionnaires and teacher journal was used to generate a description of the social milieu in the laboratory. The dyads videotaped in the two isolated rooms limited their exchanges to each other, as Mike explained "we really didn't do much [visiting]. We had the physical barrier of the door. I think the only group we really did talk to was the group in the other room" (AS1131099).

Over four lessons Mike and Ivan went into the adjoining room three times, at the teacher's suggestion, to learn how Dyad C conducted certain experimental procedures. In turn other students or dyads visited them just four times. The pattern for Dyad C was similar. So the dyads that worked in isolation had minimal interaction with other students. However, in the main laboratory exchanges were much more frequent. "You hardly ever get 20 people every single person working all the time" explained Alan (AS1021199). From the teacher's observations the students remained on task until the second half of the fourth lesson, when a number of groups drifted into informal chat. This was the result of a class management issue that will be expanded on in section 4.4.4. One half of the responses about interactions between dyads were similar to Denman's (AS1021199):

> Groups of two were good, because we still got to talk to the groups next to us. We talked to the other groups quite a lot. Most of the communication between groups was exchanging data, results, ideas . . .

All of the evidence suggested a collegiate atmosphere prevailed within and between groups. Students such as Shauna and Tina were more self-reliant when it came to sharing ideas:

> Teacher: Did you find you spoke to other groups very much?
> Shauna: Yes, to see if we were doing the right thing mainly.
> Tina: But we didn't really compare our ideas. We did check that our graphs were doing the same sort of thing.
> Teacher: You checked techniques more than ideas?
> Tina: Yes. (AS1131099)

When asked if they would have preferred traditional laboratory experiments or formal lectures, the tenor of responses was that students valued the freedom the MBL gave to experiment on their own terms. "I think it is good to have independent sort of work," not the "boring" traditional experiments (Tina, AS1131099). "By doing this we get to make our own observations, and to work out whether we are right or wrong, and what we would do differently if we repeated the experiment" (David, AS1121099). Simon contrasted the atmosphere in the MBL, to regular lessons with the "teacher talking like a fire hose into a cup" (AS1021199), leaving very little knowledge retained.

Social constraints within the MBL, from the teacher's observations, were principally those of self-control students exercised to remain on task. The demands of the POE procedures were exacting. As Mark said (AS2071099)

> Because if you are left to do it on your own, you think: "Oh bugger the predictions, just go ahead and do it and fill all of that out later." Whereas with this [the POE notes to be completed] you are forced to make a prediction before you start and then see what happens, and try to figure out why it happens.

So students exercised their freedom in the laboratory as a relative freedom, and there was no evidence of resistance to or dissatisfaction with their laboratory activities.

4.4.2.2 Discussion

The above analysis of student discourse began with selected passages of dialogue that illustrated activities and techniques students used to complete their tasks. The analysis concluded by examining data pertaining to the affective and social conditions in the MBL.

Assertion T6. Learning conditions in the MBL were conducive to fostering conceptual change, the conditions being: graphic evidence to engender dissatisfaction with prior conceptions; opportunities to construct new conceptions that were seen to be intelligible, plausible and fruitful; and an atmosphere that was motivationally and socially conducive to constructing new understandings.

Conceptual change theory (CCM) developed in the early 1980s (Duit & Treagust, 1998) suggested there were four conditions that fostered conceptual change. There must be dissatisfaction with present conceptions, and new conceptions must be intelligible, plausible, and fruitful. CCM has been used fruitfully in science education research and physics instruction (Tao & Gunstone, 1999; Thorley & Stofflett, 1996). In recent times CCM has taken into account the important roles of affective (motivational), social and contextual factors in the classroom. In their critique of CCM, Duit and Treagust (1998) observed:

> Conceptual change has to be viewed as a process of bewildering complexity that is dependent on many closely interrelated variables. Conceptual change . . . has to be embedded in "conceptual change supporting conditions," including the motivation, interests and beliefs of learners and teachers as well as classroom climate and power structures. (p. 15)

The interpretive analysis of student dialogue gave evidence of students being given opportunities to predict, confront discrepant results, exchange ideas, and scaffold their knowledge. No attempt was made to categorise or quantify students' conceptions and conceptual changes, rather to describe moment by moment their learning experiences. Assertion T6 is grounded in the analysis for this class of students. The first four of these conceptual change supporting conditions are closely associated with the student activities illustrated in the vignettes analysed. Of course these activities are set contextually in the classroom.

Assertion T7. Within and between groups, students engaged in a broad range of activities to create and interpret graphs.

These activities included:

- Evaluating the display to confirm or disconfirm predictions.
- Making new short-range predictions during experiments.
- Theorising, based on personal experience, comparisons, results of previous experiments, or textbook information.
- Expressing agreement, disagreement, and self-correction.

- Interactively scaffolding understanding, correcting a partner, counterbalancing opinions, and resolving conflicts.
- Note-taking to maintain a record, to crystallise thinking, or to complete earlier experiments.
- Adjusting experimental apparatus to obtain feedback from the display.
- Trialling ideas, predicting and proposing new experiments.
- Crosschecking graphs and techniques with other groups or the teacher.
- Predicting with the display turned off.

The graphs that students create are conceptual models, from which students extract elements they consider relevant, relate them to what they know, and construct mental models (hopefully) consistent with the new information (Greca & Moreira, 2000). Selecting and manipulating data from the display occupies much of students' time in the MBL, and is part of the modelling process which students of physics learn as they gain experience. The data analysis presented examples of students working, sometimes separately, mostly cooperatively, from the display.

> <u>Assertion T8.</u> The display served as a shared resource for joint knowledge construction.

The MBL display is thus seen to play an important role in enabling students' social construction of knowledge, as discussed in section 2.4.3.

From the display the students used steps and rules to:

- Verify existing beliefs.
- Identify patterns, trends or comparisons.
- Formulate theory.
- Answer set questions.

In the process they:

- Selected a feature for evaluation, analysis and explanation.
- Used the screen as a working diagram against which they held straight edges, measured maxima, minima and changes; estimated ratios and identified proportionalities; calculated gradients, time constants and specific heats; compared multiple graphs; matched data from tables with the graphs; and extrapolated. A single graph was subjected to as many as four distinct mathematical analyses to sustain discussions.

- Made progressive interpretations of graphs as they developed during the experiment.

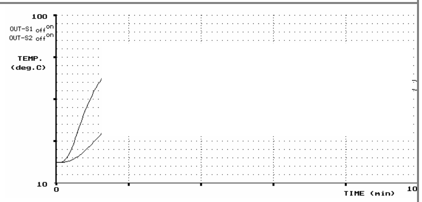
4.4.3 Teacher interactions with dyads

The teacher's roles during MBL activities are to provide technical support and to facilitate learning. This section examines how student-teacher interactions mediated learning and maintained the technical requirements of the MBL, based on data from the annotated transcripts of video/audiotapes of dyads, teacher audio recordings, student interviews and student questionnaires.

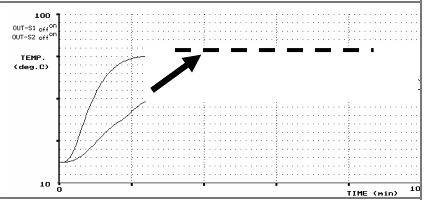
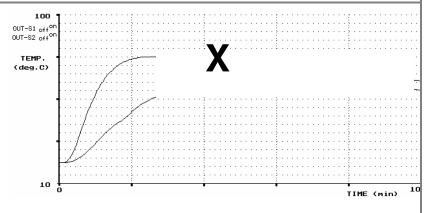
4.4.3.1 Analysis

The most frequent teacher interaction was that of circulating between groups and asking questions. For the purpose of the research, the teacher spent a disproportionate time with the two dyads being videotaped during each lesson.

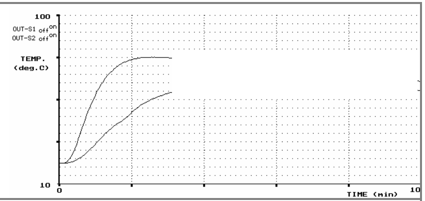
The analysis begins with a seven-minute exchange involving the teacher and Dyad A. Mike and Ivan had just begun the "saucepan metal" task (referred to earlier in a different context), which most groups had completed the previous lesson. The screen displayed the growth of two temperature graphs, using sensors placed in the top ends of copper and iron rods standing in hot water.

<table>
<tr><td>284</td><td>Teacher</td><td>Which one is which? [That is, which is copper and which is iron?]</td><td></td></tr>
<tr><td>285</td><td>Mike</td><td>That would be the copper. (Both Mike and the teacher touch the steeper graph on screen.) You can actually touch that and feel that . . . it's . . . quite hot (touching the top of the copper rod).</td><td>
</td></tr>
<tr><td>286</td><td>Teacher</td><td>What did you think prior to heating?</td><td></td></tr>
<tr><td>287</td><td>Mike</td><td>We did think that the copper would heat up first cause that's what's usually used as the base for pots . .</td><td></td></tr>
<tr><td>288</td><td>Teacher</td><td>Did you by chance work the last problem for homework yesterday?</td><td></td></tr>
<tr><td>289</td><td>Mike</td><td>I didn't really have time to do homework . .</td><td></td></tr>
</table>

The teacher feigned ignorance of the graph and inquired of Mike, who immediately associated the steeper graph with the copper rod in the beaker of hot water. Mike claimed that copper conducted better than iron based on his knowledge that some saucepans have copper bases. The teacher's query in line 288 was to learn if the students had referred to the Table of Thermal Conductivities linked to a homework problem. They were not aware of the table.

290	Teacher	That's OK . . . . . (He looks at Mike's notes) . . . . (All pause to watch the graph grow. Mike consults his notes.) . . . . . What's the graph telling you? [The copper graph is close to levelling off, the iron is still rising but only half the temperature rise of the copper.]	
291	Ivan	I think the iron's still going up . . .	
292	Teacher	What's it telling you about the copper and iron?	
293	Ivan	It seems like the copper's levelling off.	
294	Mike	Iron. . . It looks like the iron's going to reach the same point temperature there (pointing to the screen with his pencil aligned against the slope of the iron graph).	
295	Ivan	Yeah. Really (??).	
296	Teacher	So what's it telling you about the copper and the iron?	
297	Mike	The copper's reached the maximum temperature that it's going to get to . . . the iron's still (his hand rises) increasing and they're going to reach that temperature [i.e., same top temperature at X].	

The teacher's questions (lines 292 and 296) prompted Mike to extrapolate the growth of the curve for iron (lines 294 and 297). Then Ivan noticed a new development.

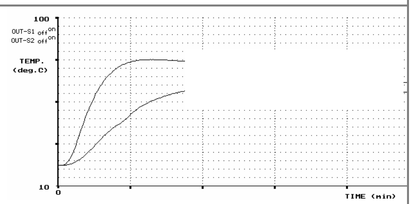
297	Ivan	Copper's decreasing. [The top line at right has started to drop]	
298	Teacher	Why?	
299	Ivan	Cause water's loosing its heat to the outside air (gesturing to the rods in the water) . . . and to the rods.	

303	Ivan	Yeah and the rods are loosing heat to the air, and the water as well [i.e., water looses heat to the air]. (Mike concurs, his words are not clear.)	

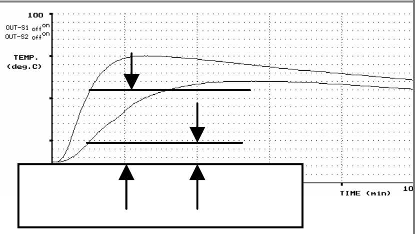
Again Ivan responded to questioning, giving an extended answer (lines 299 and 303). Whether Mike or Ivan would have voiced such explanations without the teacher's presence is uncertain. The teacher probed further and Ivan searched for an explanation at the atomic level.

304	Teacher	Yeah alright . . . How come the iron is not up to the temperature of the copper? After all, it's been in there a long time.	
305	Ivan	It comes down to the molecular level . . Does it come down to the molecular level? The atoms inside?	

Mike did not respond to Ivan's atomic theory, but recalled (line 306 below) the Table of Thermal Conductivities that he consulted a minute or so earlier (see line 290 above).

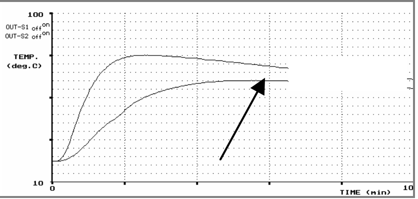
306	Mike	I think there is actually a constant assigned to (turning to Day 1 homework, with the Table of Thermal Conductivities) . . . assigned to each metal . . . thermal conductivity.	
307	Teacher	Oh you were reading that?	
308	Mike	I quickly glanced at it this morning.	
309	Teacher	Yes, alright.	
310	Mike	It is saying that each metal has a relative conductivity . . or constant.	
311	Teacher	Well now that – you're looking at that (touching table in notes) – how does that relate to what you see up there?	The table shows thermal conductivity of iron 76, copper 380 (with units)
312	Mike	It shows that copper goes up – what – four times, or so . . as iron does (looking at Table; then his eyes go to screen). I really don't know what's (?) (turns head on angle as though trying to interpret the graph shape on the screen).	

Quickly estimating the ratios of their conductivities (76:380) he proposed (line 312) that copper should "go up" four times that of iron. But he was puzzled as to how this was shown in the graphs (line 314 below).

313	Teacher	Four times? (pointing back to the Table) . . . four times – would that show up on the graph?	
314	Mike	It should (looking between the screen and his notes).	
315	Teacher	It’s closer to five times isn’t it. (Mark: = Yeah).	
316	Mike	Yeah, you take it – a line across there (touches screen, then picks up his notepaper and holds the top horizontal edge against the screen at the starting temperature, and measures vertical distances with his fingers). There is a fairly significant difference there, but it’s not quite five times is it. (Mark and Ivan both ponder the screen.)	

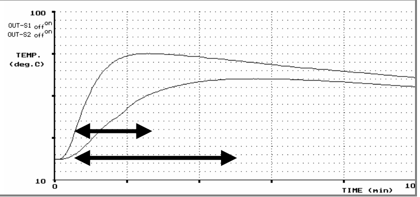
Mike made his first attempt to find the ratio of 5:1 depicted in the graph on line 316. He used the display as a working diagram and measured with his fingers the vertical temperature increases for iron and copper at the 30-second mark (shown by the arrows). He judged that the increases were “not quite five times.”

His second attempt (line 318 below) referred to a method involving time constants that he used the previous day. This technique had not occurred to the teacher, who (in line 319) gave a hint that they pursue vertical measurement comparisons.

318	Mike	You’d want to get the time . . . like find what 60 or 70 percent [a time constant value] of that is. I’m not clearly too certain.	
319	Teacher	So what you’re looking at is the vertical axis of the graphs that you’re comparing at some stage . . . (Mark and Ivan ponder over the screen). Is there any other comparison of the two graphs . . . to give you that five times factor?	
320	Mike	You could draw how quickly it reaches its max temperature . . because (touching screen) iron has kind of dropped down there . . . it’s not going any higher than it is. . .	

Mike noticed that the iron line had peaked (line 320), so for his third method he suggested comparing the times for the two lines to reach their maxima.

After some pause, as neither Mike nor Ivan expanded on his ideas, the teacher focused their attention back to the "initial heating section" (line 321 below). Mike touched the screen (line 322) to show the short section for copper and the longer section for iron.

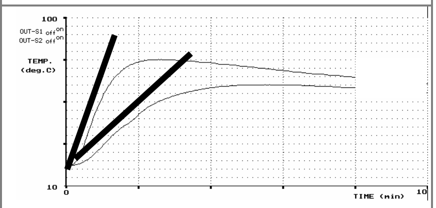
321	Teacher	Where is the – where is the initial heating section? . . . as shown on the graphs.	
322	Mike	Umm. . . (touching screen) to there with the copper, and it's still heating to there with the iron (showing the rising sections of each curve).	
323	Teacher	Alright. Now you've looked at the vertical differences between them, what other comparison could you make about the graphs . . just focusing on the initial heating section?	
324	Mike	Well the copper heated . . say twice as fast as the iron (gesturing).	
325	Teacher	How do you estimate twice as fast?	
326	Mike	You've got . . that long there to reach the maximum and that long (touching the graphs) . . but you could also look at the times . .	

The teacher had in mind that they compare gradients (line 323), but Mike's reply (lines 324 and 326) pursued his third method and compared times to reach their maxima. Mike judged from this that copper reached its peak only twice as fast as copper.

He was still unsatisfied and returned to his notes (line 328 below). Mike returned to the second method (began in line 318 above) of calculating time constants, which was "probably a more accurate way," since he had done this the previous lesson using actual measurements taken from the screen. The teacher concurred.

328	Mike	(He reads his notes reflectively.) You could also look at the time constant which is probably a more accurate way of . . .
329	Teacher	Comparing time constants, alright that's another way, yes, you could do that. The two time constants . . .

For the first time Ivan entered the discussion (line 330 below) and either originated the fourth method or took up the teacher's hint to compare gradients. Ivan's hesitancy was reassured by the teacher (line 331), but Ivan was uncertain how to apply the gradient lines (line 332).

330	Ivan	(Silent through this discussion to date, but observant and listening) I was thinking of gradient, but that . . um . . doesn't really (both scrutinise the screen).	
331	Teacher	What were you thinking about gradient?	
332	Ivan	Well the gradient is always going to be a lot more steeper but I don't know (hand on chin) how it would be in relation to the iron? (Teacher = Well, . .)	
333	Mike	(= You've pretty) much got a straight line there (touching the screen) that you could take a gradient off . . . you've got a straight line there as well. (Ivan: = Well)	
334	Teacher	How do those two gradients compare? . . .	
335	Ivan	I don't know in degrees or . . that type but . . .	

Mike (line 333) again used the screen as a working diagram and traced out two slopes on the screen. At this stage the teacher left the students to complete their explanation.

In this episode the students were stimulated to analyse and express themselves beyond what they might have done otherwise, as the discussion exceeded the actual demands of the "saucepan metal" task. They were prompted to expand a qualitative problem into a quantitative analysis. Control of the laboratory remained with the students, in that they were not directed to do anything per se. Neither did the teacher-student relationship devolve into a transmissionist atmosphere. The sequence of teacher questions was directed towards scaffolding their understanding, but even then Mike, intentionally or unintentionally, followed his own agenda. Ivan's silence during most of the dialogue did not mean he was a passive onlooker, as indicated by his insightful suggestion to measure the gradients of the lines.

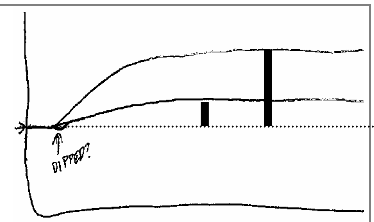
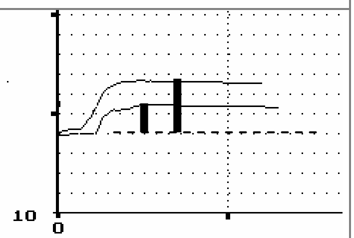
The teacher made use of "what if" questions that invited students to extend their understanding to new situations. In the following instance the teacher asked Mike and Ivan how a standard glass thermometer would compare with the MBL sensor. Mike's reply (line 127) identified the surface area of the thermometer for consideration, which in turn he associated with the time constant concept.

126	Teacher	While that's happening (the heating graph continued to grow) what would have happened if you had put this thermometer (showing a mercury-in-glass thermometer) in there instead of that sensor? (Both students think for 10 seconds.)
127	Mike	Probably got a . . going to have a higher time constant because it's got more surface to heat up, yeah (clenches fist like a bulb).

Other teacher questions were directed at encouraging students to express themselves: "Is they any point being made by what you're doing there?" Sometimes he played the devil's advocate, challenging them to defend their answers. Such questions stimulated students' to express themselves, to think about what they were doing, to clarify their thoughts, and expand their ideas in new directions.

The teacher appeared conscious of adopting a conversational style that turned directives into questions ("Have you made your prediction first?") or suggestions ("It sometimes helps to illustrate it with a graph"), or answered questions with a question. This form of dialogue helped to preserve a student-centred locus of control in the laboratory.

The teacher promoted liaisons between dyads, such as directing a group with a poor quality graph to visit a group with an exemplary graph, as seen in the next example. Due to experimental errors Dyad A created two graphs which Mike interpreted as showing a square proportionality between two variables (line 651 below). When Mike and Ivan failed see the source of their error, the teacher (line 656) suggested they view Dyad C's graph in the adjoining room.

651	Mike	It actually looks like something is squared . . to get that kind of result. [See Mike's copy of the screen graphs on the right. Mike sees one rise four times the other.]	
656	Teacher	You might find it interesting to have a look at what some of the other groups have got, see (gesturing to door)? (Both get up and go out for 1 ½ minutes.) [See Dyad C graphs for the same experiment. One rise is only twice the other].	

The teacher's role as listener and guide limited his level of intervention. There were instances where he intentionally allowing students to follow "blind alleys" (Roth, 1994), such as associating the thermal energy content of a body with its surface area or density, or the belief that slow-cooling materials were "able to contain their heat energy for longer"

(Selina's POE notes, p. 6). Selina continued to associate the heat content of a body with its surface area through the third day, until she was introduced to specific heat in her homework that evening. On the fourth day she changed her experiment explanations to reflect accepted theory. In the cases of those students videotaped, misconceptions apparent in the first few days were self-clarified by the fourth day.

An answer was sought to the question: Was the level of intervention and nature of explanations by the teacher acceptable to students? According to the interviews and questionnaires, the answer was "yes." However, one third of the students reflected Tyson's comment: "I would like to learn through experimenting but maybe have a conversation session after every lesson, so as to reflect on our experiments." The sequence of four MBL lessons allowed for only a brief introductory discussion about the results of the previous lesson. This issue will be addressed in the following section.

The teacher's speech and actions (or lack thereof) at times constrained students' learning. On occasions he failed to respond to students' procedural errors, such as Mark and Shaun's mismeasurement of time constants. This was an instance in which the teacher needed to explain how a certain quantity was measured, how to use a technical tool as it were. His conversation with students sometimes assumed, incorrectly, that they had reached a certain stage with their tasks. For example, his advice to Mark and Shaun "After you've finished that get onto the friction one" (Dyad B line 278) meant that by taking his advice they bypassed a key task, leaving an important gap in their sequence of experiments. On three occasions in speaking with Dyad A the teacher introduced concepts that were irrelevant or beyond the students' comprehension. In point of fact the videotapes showed this did not constrain their learning, for as soon as he left they continued their tasks as though uninterrupted. At most they lost time from their experiment.

About one half of the teacher's dialogue related to providing assistance with laboratory equipment, experimental techniques, and clarifying the requirements of the POE worksheets. This was in response to students' requests, or of his own originality, as he circulated from group to group. He offered suggestions to help students use time and equipment efficiently, thus allowing them more time to discuss the experiments.

4.4.3.2 Discussion

> <u>Assertion T9.</u> When the teacher asked probing questions, they often stimulated deeply processed responses linked to graph features and the experimental phenomena.

The researcher in his role as teacher stated (section 3.3.5.3) that one of his roles was "to listen to students and act as a facilitator by the use of appropriate questions." The first part of the analysis in this section presented such an example, one of eight similar conversations. In section 4.3, Table 4.1 listed a number of dialogic characteristics used by students to process ideas at a deep level. These featured in the students' dialogue when drawn out by the teacher. To reiterate, they constructed explanations, judged features of graphs, used the screen as a working diagram, made extended calculations, appealed to the graph to support their claims, expressed puzzlement, and searched for alternative data to support their claims. The assertion does not imply that without the teacher the students would otherwise not have interacted at a deep level. The assertion is made that, by means of appropriate questions, the teacher promoted dialogue in the MBL that was conducive to better learning.

The second aspect of the teacher's activities was to maintain the technical support on which students depend. An absence of expressions of student frustration with data collection and display suggested that, from their viewpoint, the teacher was successful in maintaining conditions conducive to learning. The history of MBL shows this has not always been the case (Clark & Jackson, 1998; Rogers, 1987; Roth et al., 1996; Scaife, 1993) due to hardware and software factors.

4.4.4 Student limitations and delimitations in the thermal physics MBL

The analysis of data thus far has revealed that a number of difficulties and constraints hindered some students' conceptual development. Rather than quickly ascribe these to students' personal limitations, the question was asked: What external factors constricted their learning conditions in the laboratory? This section seeks to identify some of the delimitations within which they operated. The data sources for this analysis were the student POE worksheets and transcripts of dialogue.

4.4.4.1 Analysis

The first example involved the final task, which required students to synthesise a range of concepts from previous experiments.

> Task 10: What is the relationship between the amount of heat energy added to a body and its temperature rise? What factors are involved? These questions call for a number of experimental trials.

Complete data were available from seven groups, of which only four had a high level of success. All POE worksheets for Tasks 6 through 10 were read, and all of the students' predictions, explanations, conclusions, and use of terms specific to thermal physics for the task were tabulated. The results appear in Table 4.3.

Table 4.3

Terms and References Used by Dyads in Task 10

Dyad	A	B	C	D	E	F	G
Student 1	FTS	FTSM	Md	Mda	dh	FTSM	SMavc
Student 2	FTS	TM	Md	no POE	(nil)	FTSMv	SMvc
Student 3					Md		
Task 10 level of success	High	High	Low	Low	Low	High	High

Key to terms and references used in the table.

Factors relevant to the task	Factors not relevant
F used formula $Q = mC(t_1 - t_2)$	d referred to density
T used Table of Specific Heats	a referred to surface area
S used term specific heat	v referred to volume
M referred to mass	h used term thermal contact
	c used term thermal conductivity

Table 4.3 shows that four groups had a high level of success with this task. Three of these groups (A, B and F) made use of multiple relevant terms and data sources. The fourth, Group G, intentionally considered and eliminated irrelevant factors (such as surface area, density and volume), and then used two of the relevant factors (specific heat and mass) to arrive at a sound conclusion. The three unsuccessful groups showed a limited understanding of the factors involved. None of the three mentioned specific heat, and only these groups claimed that the density of the material (an irrelevant factor) affected its temperature rise.

The single factor that distinguished the four successful groups was that these students knew how to apply the term "specific heat," or referenced the Table of Specific Heats attached to the POE worksheets for Day 3. These students, of their own initiative, used the Table as a resource from which they constructed explanations for experiments on Days 3 and 4. On Day 3 some students read the attachment while waiting for graphs to finish, realised its association with the experiment at hand, and included specific heat data in their explanations. Other students first read the Table when completing homework on the evening of Day 3. All successful students used the concept of specific heat for Day 4 experiments.

As students adopted new terms, their predictions and explanations in later experiments advanced to higher levels.

A similar situation arose on Day 1 with the Table of Thermal Conductivities attached to the POE worksheet. Students who read this table during the progress of the experiments used the information to construct more profound explanations than the other students.

The second example for analysis concerns a student who brought additional resources to the laboratory. Peter explained why a 100 g block of aluminium contained more heat energy than a 100 g block of copper (both at 100 ^{0}C):

> Although Cu and Al were of the same mass, this does not mean that each sample contained an equal number of atoms. The Al has a lower molar mass therefore it has more atoms. Therefore it will have more heat energy than the Cu. Therefore it heats the water [in a calorimeter] to a greater degree. (POE worksheet, p. 14)

Peter drew on his exceptional knowledge of physical chemistry and concluded that heat energy content related to the number of atoms in the sample of material.

The third example for analysis concerns Dyad A, which lost considerable time with Tasks 6 and 7 due to not understanding how to use a calorimeter. Despite the teacher's discussing and demonstrating the use of a calorimeter prior to the videotaped lessons, it was evident his presentation was inadequate. Consequently Mike and Ivan recorded poor quality data on Day 3. When Mike analysed the data quantitatively he arrived at a wrong conclusion, that was adjusted only after the teacher suggested they view the more accurate data obtained by Dyad B.

The fourth example of delimitations was the difficulties students occasionally encountered when they forgot to save data to disk for later recall. This was a shortcoming of the software, which should be written to anticipate user errors.

The fifth example relates to the structure of the lessons. The sequence of four consecutive laboratory lessons was based on the availability of recording equipment for purposes of the research. The first extended opportunity students had to share their results and conclusions as a class came in the lesson following the four lessons in the laboratory. A number of students said in interviews and questionnaires that they would have preferred an extended whole-class discussion after each laboratory lesson. They said that this would have helped them consolidate new concepts from each lesson, before progressing to the next.

Tina suggested: "I think a mix of this sort of work and teaching, say a few days of experimenting then teaching on the correct answers and theories." (AS1131099)

Finally, student fatigue appeared to be a factor limiting students' concentration during the 70-minute lessons. In four of the eight lessons videotaped, during the last fifteen or so minutes, one or both of the students appeared tired and listless. For example, towards the end of Day 3 John repeatedly expressed his tiredness, looked at his watch, and let David carry the conversation. In two of the videotaped lessons the students yawned and stretched as they viewed the graph over extended periods. Ivan appeared excessively tired at the start of a hot midday lesson, having just returned to school from an exhausting geography excursion. However, the degree to which fatigue restricted interaction or mental acuity can only be surmised from the videotapes, and the issue was not probed in the interviews.

4.4.4.2 Discussion

> Assertion T10. The message taken from the display, and subsequent canonicity of science understanding, is delimited by the resources students bring to and draw on during the experiment.

One conclusion to be drawn from this analysis relates to the observation by Duit and Treagust (1998, p. 15), that:

> New conceptions do not become intelligible and plausible to students, who are unable to understand the new view because they do not posses sufficient "background knowledge." Without a certain amount of background knowledge, the arguments in favour of the new conceptions might not be understood.

Some students brought more "background knowledge" to bear on their experiments than others, by reason of reading worksheets, completing homework, and having an extensive knowledge of science in a related area. Resources also include students' expertise with experimental techniques, seeking assistance from peers and teacher, and practised familiarity with the software. The students are screened from these latter delimitations, until such times as their resources expand. Awareness of delimitations may be precipitated by interactions with others in the laboratory, a chance reading of literature, or consequent on the analysis of the display.

A corollary of Assertion T10 is that the potential of the display to convey richer and more canonical meaning is enhanced as students increase their experimental skills and conceptual insights.

> Assertion T11. Student learning is delimited by the teacher's preparation for and structuring of the MBL lessons.

The last four examples in the analysis related to delimitations that devolve around the teacher. The assertion infers two ways to improve learning in this MBL: (a) The lesson structure should alternate short periods in the MBL with whole-class discussions, and (b) experiment preparation should include continuous refinement of the MBL software, and extended prior practice by the students with the MBL materials. Interspersing experiments with class discussions affords students opportunities to consolidate their understanding before proceeding to the following MBL tasks. This also may confer a benefit in relieving student fatigue. Since the teacher-researcher authored the software used in the MBL, it is possible for him to make refinements as necessity indicates. This is not the usual situation in MBLs, as the software used is produced by commercial sources.

4.5 A SUMMARY OF THE THERMAL PHYSICS MBL

This section began by identifying the actors in the MBL, and then described the network relationships between them (Figure 4.1). For each task the dyads progressed through five stages: (a) understanding the problem and predicting, (b) setting up and commencing the experiment, (c) collecting data and observing, (d) analysing, and (e) explaining the results. Frequently students combined the first two stages, and for longer experiments they repeated cycles of the last three stages. The networks associated with observing, analysing and explaining experiments and graphic data (shown separately in Figure 4.1 and combined in Figure 4.2) showed that the medium of the computer display was central to an interactive process involving students. This is in contrast to a picture of learning taking place as a result of unidirectional instruction "delivered" by the medium or an instructor.

The chapter then examined the role of the display in students' conversations, and teacher-student interactions, a summary of which is presented in Table 4.4 (following) as 11 assertions. Finally, the chapter discussed some of the delimitations to student learning in the MBL.

The same procedures used for the analysis of Part 1: Learning About Thermal Physics in an MBL are repeated in Part 2: Learning About Kinematics in an MBL. There was no reason to alter the research questions from those guiding the analysis of Part 1. A comparison of these two parallel studies will be reserved for chapter 6.

This completes the discussion of learning about thermal physics in an MBL. The next chapter will now turn to an analysis of kinematics, to be followed by a discussion of features common to thermal physics and kinematics MBLs, as well as some of their differences.

Table 4.4

Assertions From the Analysis of the Thermal Physics MBL

The role of the display in students' dialogue
Assertion T1. Students viewed the display (a) predominantly, as representing the experimental phenomena, (b) as associated with other conceptual models related to the experiment, and (c) as a graph in its own right.
The level of student-display interactions
Assertion T2. During student-display interactions, while students' activities ranged from fulfilling basic requirements to deep level cognitive processing, the dyads completed the majority of tasks at a deep level of mental engagement.
Assertion T3. Students' deep approach to learning was supported by the enduring nature of the display.
Assertion T4. During data logging, dyads generally engaged in multiple on-task activities related to making meaning of the graphs.
Students' assessment of graphic data
Assertion T5. Students critically evaluated the appearance of the graphic display.
Dyadic discourse and graph interpretation
Assertion T6. Learning conditions in the MBL were conducive to fostering conceptual change, the conditions being: graphic evidence to engender dissatisfaction with prior conceptions; opportunities to construct new conceptions that were seen to be intelligible, plausible and fruitful; and an atmosphere that was motivationally and socially conducive to constructing new understandings.
Assertion T7. Within and between groups, students engaged in a broad range of activities to create and interpret graphs
Assertion T8. The display served as a shared resource for joint knowledge construction.
Teacher interactions with dyads
Assertion T9. When the teacher asked probing questions, they often stimulated deeply processed responses linked to graph features and the experimental phenomena.
Student limitations and delimitations in the thermal physics MBL
Assertion T10. The message taken from the display, and subsequent canonicity of science understanding, is delimited by the resources students bring to and draw on during the experiment.
Assertion T11. Student learning is delimited by the teacher's preparation for and structuring of the MBL lessons.

CHAPTER 5: LEARNING ABOUT KINEMATICS IN AN MBL

Kinematics is an introductory topic in almost all physics courses, and instruction in kinematics has featured in early MBL research (Barclay, 1986; Beichner, 1990; Brasell, 1987; Linn et al., 1987; McDermott, 1991; Thornton & Sokoloff, 1990).

A number of intuitive graphing conceptions held by kinematics students are well known (McDermott, Rosenquist, & van Zee, 1987). For example, students confuse the mental pictures of objects as they moved up and down hills, with their corresponding displacement-time and velocity-time graphs (termed graph as picture confusion). They see increases in speed, for example, as a hill in a graph. A second error is to confuse information conveyed by the height of a graph with regions of maximum slope (slope/height confusion). The structured POE tasks for kinematics had the potential for confronting students with these conceptions.

The Year 11 introductory physics class of 5 girls and 24 boys was particularly large, contrasting with the class of 15 students that participated in the thermal physics study. Their ratings for general science studies in the previous year were: 13 achieved at "A" standard, 11 at "B" standard, and 5 at "C" standard, where "C" was a passing grade. For the laboratory lessons they combined as seven dyads and five triads using the same laboratory arrangements as for thermal physics (see the plan in Appendix 3), only using 12 computers.

Whereas the students in thermal physics had prior familiarity with MBL and POE methods, this class had studied physics for only four weeks. During that time they completed two non-MBL experiments using a POE approach, and three dyads were selected for special study based on their ability to express themselves verbally and through POE notes: two girls, two boys, and a mixed couple. Two pairs were self-selected as friendship groups, and the mixed couple was asked to work together to make up the final dyad. They were (using pseudonyms): Mel and Hank (Dyad A) for all four lessons, Kate and Sue (Dyad B) for the first three lessons, and Jane and Tony (Dyad C) for the fourth lesson. Based on class assessment at the end of the semester, Mel and Hank ranked 4th and 21st respectively, Kate and Sue ranked 9th and 10th, and Jane and Tony ranked 17th and 1st, in the class of 29 students.

The students participating in the present research had limited prior experience drawing pencil-on-paper distance-time graphs and using simple formulae to calculate speeds. They were unfamiliar with vectors, which means they did not differentiate between displacement and distance, or velocity and speed. In the weeks before commencing kinematics the students experimented with forces as an introduction to the directional nature of vectors. During their first lesson in kinematics, the students were introduced to the idea of displacement as a vector. None had used MBL methods for motion studies. The teacher discussed how to use POE methods effectively and then demonstrated the MBL hardware and software using a wheel sensor. The students practised using the equipment for half an hour, collecting and displaying data as displacement, velocity and acceleration graphs. During the four lessons groups completed eight tasks at their own pace, and for homework completed graded quantitative and qualitative problems relating to each day's activities (see Appendix 10).

The primary source of data for research was the transcriptions of the audiotapes annotated with descriptions of actions and expressions, and features of the screen display, taken from the videotapes. Supporting data sources included audiotapes of semi-structured student interviews, the teacher's daily journal, and copies of a mid-semester examination based on a format similar to the POE notes. The data analysis procedures for kinematics were approached in the same way as for thermal physics.

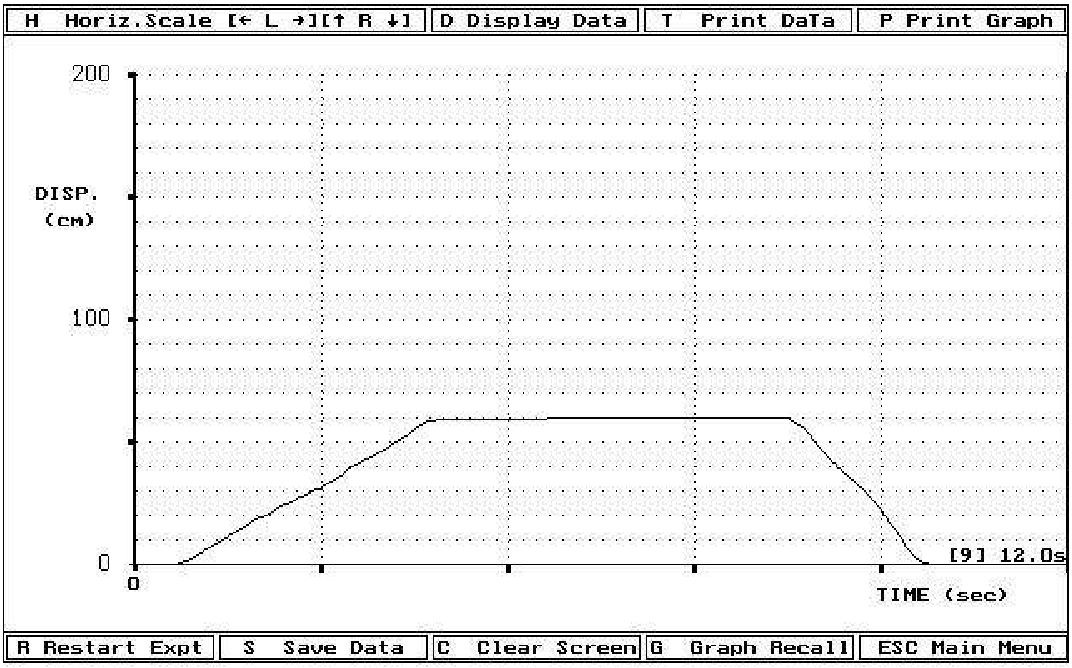
5.1 PATTERNS OF INTERACTION IN A KINEMATICS MBL

5.1.1 Identifying and illustrating network relationships

As with thermal physics MBL, the actors in the MBL were the same: students, teacher, computer display (with its generating software), experimental apparatus (including the interface and sensors), and worksheet/POE notes.

Tasks in kinematics were of two types, which for the purposes of this analysis are labelled Type I and Type II (Figure 5.1). Type I tasks involved performing an experiment using the wheel to collect data. The students translated a narrative problem into a planned series of wheel sensor movements, generally executed by moving a hand-held wheel sensor on the bench top to create a displacement graph. Type II tasks involved starting with a displacement graph and predicting the corresponding velocity and acceleration graphs. With a change of screens, the velocity and acceleration graphs were displayed. This type of task involved no bench top experiments.

(a)



(b)

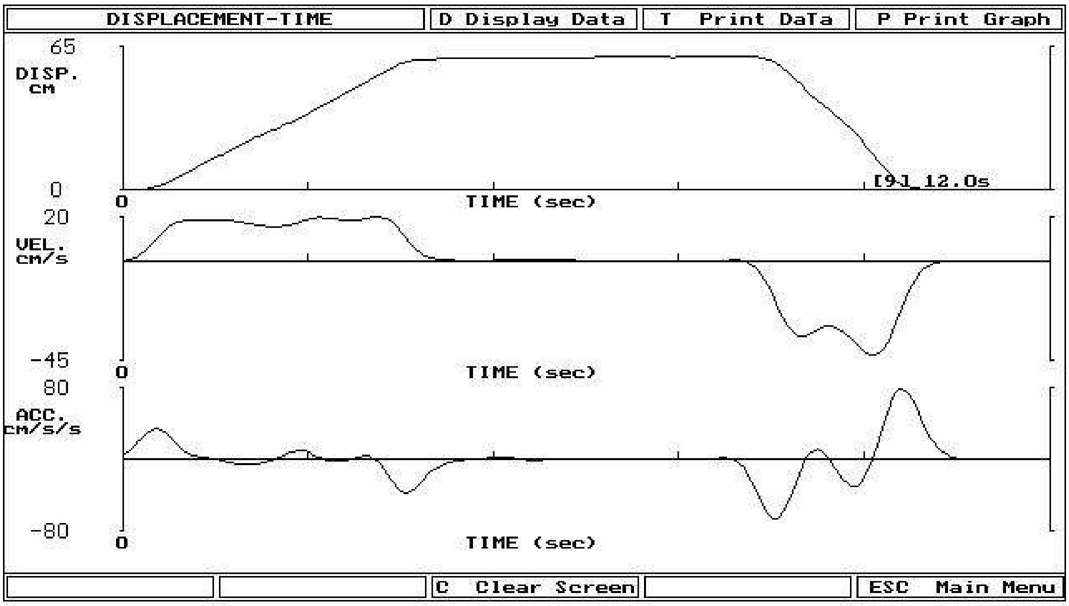


Figure 5.1. (a) For Type I tasks students conducted experiments to collect data and produce displacement graphs. (b) For Type II tasks students began with a previous displacement, from which they predicted velocity and acceleration graphs.

The transcripts were read to identify the stages through which students progressed, and the results were the same as those identified in thermal physics (see Figure 4.1). The stages closely identified with the requirements of the predict-observe-explain format used by the students. These were: (a) understanding the problem and predicting; (b) setting up the experiment and display; (c) collecting, observing and assessing the graphic data; (d) analysing; and (e) explaining and recording the results. The third stage (c) was repeated until the students were satisfied with the form of the graph. The last two stages (d) and (e) were closely linked as students often wrote explanations while analysing sections of a graph. The five stages and the links between them are displayed in Figure 5.2.

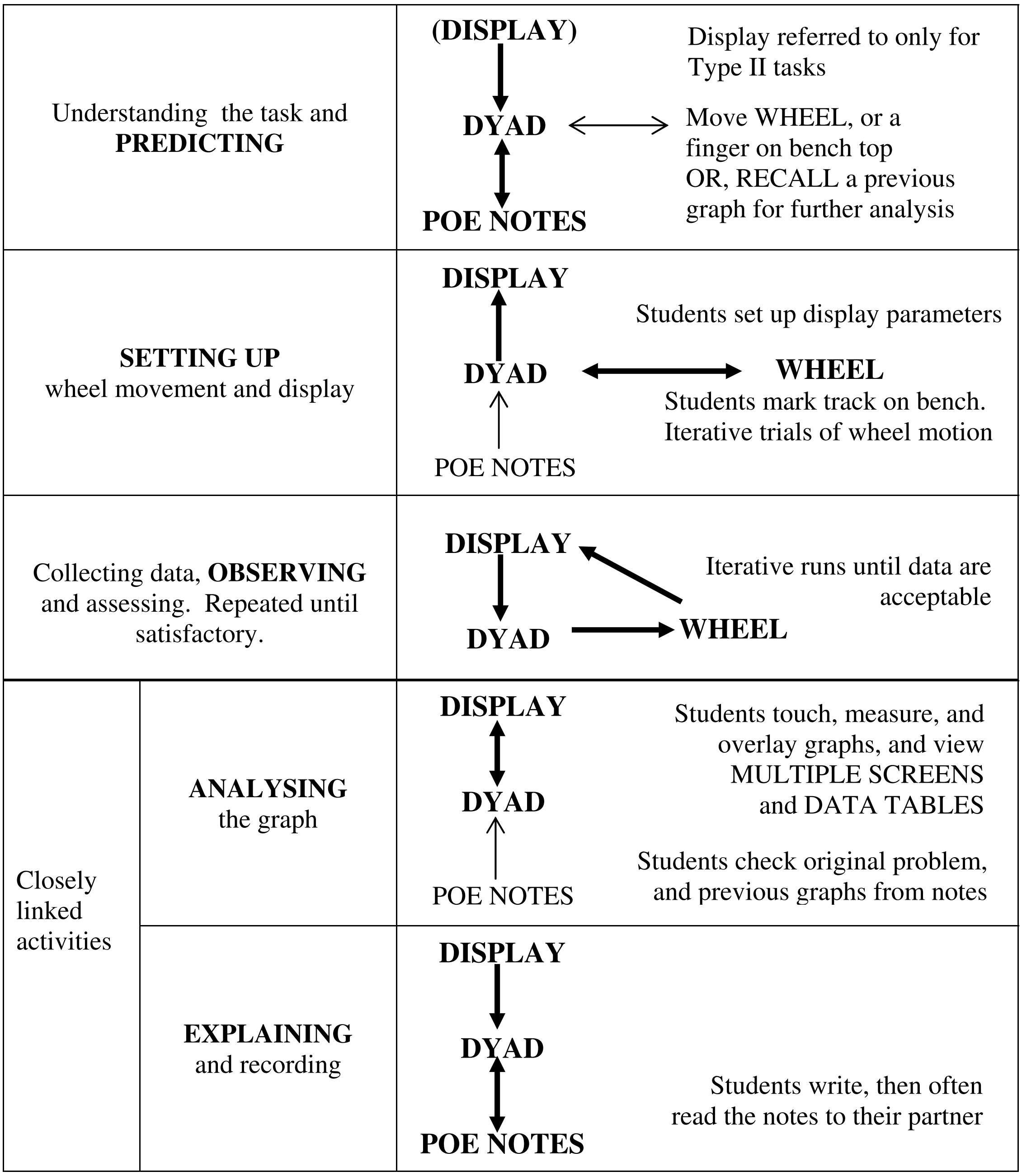


Figure 5.2. Networks of interactions during kinematics tasks, showing five stages through which students progressed in handling tasks.

The right-hand column illustrates the network relationships that commonly occurred between the actors at each stage. The boldness of the type indicates the significance of the actor. The thickness of the arrows indicates a judgment made as to the frequency of the flow of information from an actor, or attention given to an actor. Arrows indicate speech, reading, a gesture, viewing, writing, feeling, setting up, or sending as an analog signal. Within the dyad continual exchanges took place by conversation, cooperative actions and non-verbal messages. The teacher is omitted from this diagram, although he spoke to the three videotaped dyads on 35 occasions during the four lessons. The videotaped dyads were visited 16 times by students from the main laboratory, and on two occasions Dyad A visited other groups.

The network for kinematics (Figure 5.2) differs from that for thermal physics (Figure 4.1) in a few ways. For thermal physics students frequently made predictions coincidentally with setting up the experiment; whereas for kinematics they made their predictions before picking up the wheel and setting up the experiment. For thermal physics the stages of collecting and observing data, analysing and explaining were often combined in an iterative process over many minutes; however with kinematics experiments collecting and observing data lasted a few seconds. Following this, students frequently combined the last two stages in an extended period of analysing and explaining.

5.1.1.1 Understanding and predicting

For Type I tasks students translated the task to a series of movements with the hand-held wheel on the bench. Sometimes they conceptualised the problem by moving their finger or the wheel back and forth on the bench to determine the direction, speed, and number of seconds needed for the motion. Their interpretation of the problem affected their prediction, which was always in the form of a displacement graph.

The following vignette shows that understanding and interpreting an apparently simple task often led to an extended discussion. Hank and Mel began the following task:

> Task 4.4. A cyclist starts from rest and cycles up a steep hill. She pauses for breath, then coasts back down the hill to her starting point.

Hank noted a similarity (stated in line 456 below) between this and their previous task (not analysed here), in which a cricketer ran the length of the pitch and returned for a second run. Both students recognised that negative velocity was involved when the cyclist returned to her starting point, but Mel (line 459) saw the conflict that she (both refer to the cyclist as “he” in the dialogue) would have to run backwards to return to zero displacement, whereas in real life she would turn her body 180^0 and keep running “forwards.” Mel modelled the motion by tracing the path on the bench top. Hank explored alternatives (line 460), that her wheel turn backwards, or (by inference) that she descend on the other side of the hill.

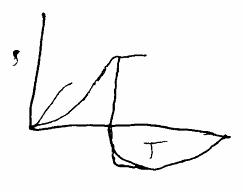
456	Hank	Would this one be similar to the last one? [Problem 4.3, in which a car starts at green light, then stops at red light.] . . Where he rides up, and then where he accelerates and stops and then decelerates.
457	Mel	This one’s like it’s got negative displacement or negative velocity, so . .
458	Hank	Oh yes cause he’s going back down the hill.
459	Mel	Yeah . . Well it’s a bit of a hard one to guess . . . he’s still going forward (Mel traces uphill with two fingers, then turns his fingers around to return to the start) . . but he’s going down where he’s already been (tracing a line back to start on the bench) . .
460	Hank	Yeah so he would – would the wheel be going backwards? . . Does he go – does he go up – does he come down the same side of the hill? . .
461	Mel	Hmm . . Yeah he goes down the same back – the same side of the hill.

For the second time Mel (line 463) traced a path on the bench and rotated his hand 180^0. Hank disagreed with the rotation idea and preferred to move the wheel backwards (line 464).

463	Mel	He’s still facing forwards (Mel again moves two spread fingers along the bench, stops, reverses the two fingers, and retraces to the start) . . so we go (towards the right on the bench) . . pause . . (reverses fingers and returns to start).
464	Hank	Yeah but the velocity – I mean the displacement would still be zero . . [i.e., she returns to start].
. . .		
467	Mel	The next one (Mel has read ahead to Problem 5) where she goes down the other side would be [i.e., displacement greater than zero] . .
468	Hank	Hmm.
469	Mel	Yeah OK no worries.

Mel read ahead to the following Task 4.5 (line 467) in which the cyclist coasted down the opposite side of the hill, and drew a contrast with Task 4.4. Mel then accepted Hank’s interpretation of the wheel movement (line 469). Conceptualising the task often took a considerable time, and usually they predicted their displacement graphs after they agreed on their interpretation of the task.

The task in the second vignette was to analyse the motion of a ball rolling down a ramp and rebounding from a wall. Mel visualised the motion by tracing his finger on the bench (line 901), and Hank used the wheel (line 904).

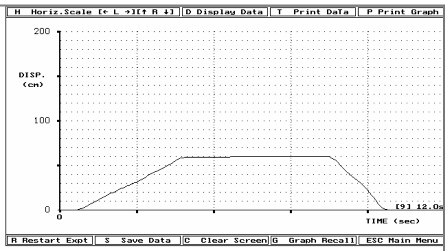
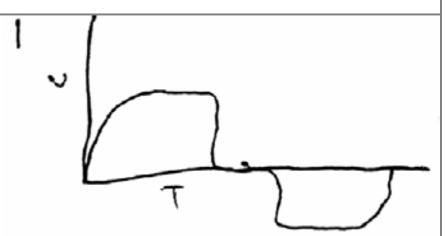
900	Hank	(Hank reads the task. Mel draws his s-t graph prediction, at right.) . . Displacement . . It'd come back to its starting position. . .Is that a displacement or (???).	
901	Mel	Yeah . . . (Mel traces the motion on the bench and then continues to draw his velocity prediction graph) . . .	
902	Hank	Have you finished your prediction?	
903	Mel	Yeahup.	
904	Hank	(He picks up the wheel.) Umm . . down the slope . . It'd slow down to about there (touching the rubber block in the diagram for Task 6).	

Now with more experience they completed this stage very quickly and moved to the second stage, setting up the experiment. As always, predictions were presented as graph sketches (as in line 900 above).

Type II tasks began with motion data collected in a previous experiment, in which case the data were recalled to the screen as a displacement-time graph, and a prediction was made based on the display. Mel and Hank began Task 5.

> Task 5. You created displacement-time graphs for the five situations described in Task 4. You can recall the displacement-time graphs you saved, one at a time, and predict their corresponding velocity-time graphs.

Mel recalled a previous graph to the display (line 749), from which they made their prediction (line 751).

749	Mel	(He read Task 5A) . . . . . . (He then displayed the displacement graph from Task 4.1.) OK. I'm going to retrieve the graphs from Task 4, for Task 5A.	
750	Hank	Oh rightee.	
751	Mel	And then we've got to predict the velocity-time graphs. (Mel displays Task 4.1 displacement graph on the screen, and from this draws a graph prediction in his notes. Hank begins also.)	

Such tasks by-passed the stages of setting up the experiment and collecting data, as shown in Figure 5.2.

On the first day students from all groups occasionally forgot to complete their predictions. Sometimes the data were so easily collected and displayed that the students produced and viewed the graph before realising they had forgotten to make a prediction.

5.1.1.2 Setting up the wheel movement and display

After agreeing on their interpretation of the problem and sketching a prediction, the students planned the space on their bench top to maximise the wheel range of movement. Some tasks referred to a cricket pitch or traffic lights, leading students to draw these features on the bench in pencil, and an arrow showing positive direction. Students were quite exacting with this stage in order to obtain acceptable data.

For example, after completing their predictive sketches for Task 4.3, Mel practised four trial runs with the wheel, assisted by Hank, until they were satisfied.

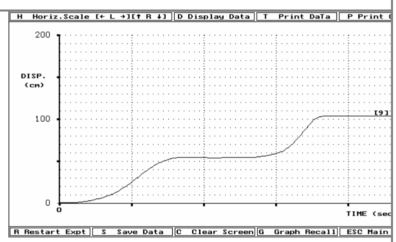
410	Mel	(He sets up graph screen, takes the wheel, and measures a space on the bench.) Right so we've got 10 seconds all up . .
411	Hank	(At the keyboard) Is it at start – at the origin?
412	Mel	Yeah. . so we accelerate for four (he practises the first run) . . . . 1 2 3 4 [seconds].
413	Hank	Constant for two – it's terribly hard isn't it . . just go really (slowly) . . .
414	Mel	About five seconds – five seconds (after a second practice he gets it right, then changes the time line on the graph to 5 seconds).
415	Hank	So is it going to be stopped [that is, at the end of the run]?
416	Mel	Yeah.
417	Hank	Isn't it ten [seconds] total?
418	Mel	Oh we could have a ten but then it'd be like umm . . . 1 2 3 4 1 2 [seconds counting] (He runs the wheel along the bench a third time but over-runs the end) . . so I think ah four – five seconds (rewinding the wheel) . . do you reckon?
419	Hank	Yes . . 2 accelerating, 1 at the speed limit, 2 decelerating.
420	Mel	Alright, how about we have ah . . 2 to the speed limit, because ah. . .
421	Hank	Yeah.
422	Mel	Like 1 2 1 - OK 1 to the speed limit [a fourth practice run].
423	Hank	Yeah.
424	Mel	(Resets graph) . . 6 [seconds].

The trials determined the time for data capture, and the display was set up (line 424) for a six-second displacement-time graph. The students found that by planning carefully, they needed only one experiment to capture good data.

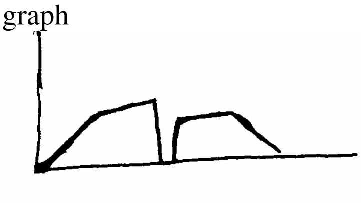
These two stages, understanding/predicting and setting up the experiment, are part of a modelling process, "the physicist's main activity" (Greca & Moreira, 2000). Greca and Moreira define this as the learning of a series of steps to identify salient elements of a system, and to evaluate, according to rules, the chosen model. The students bring together knowledge from prior experiments and their interpretation of the narrative problem to make a prediction. After practising a simulation of the task, they proceed to the next step.

5.1.1.3 Collecting data, observing and assessing

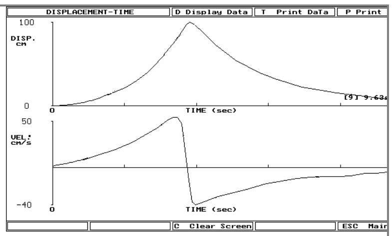
Actual data collection was very brief, and students repeated this step until the display satisfactorily represented their expectations, or they changed their expectations. Their requirements for acceptance included the graph line largely filling the screen, and its degree of fit with their predictions. Approval of the result was usually immediate as shown in the following extract. Sue and Cate predicted the graph for "a cyclist riding up a steep hill, pausing at the top, then coasting down the other side." Sue's prediction is shown on line 1014. Cate collected data, viewed the screen, and accepted the data immediately (line 1017).

1014	Sue	So it's going to be that one (pointing to predicted diagram).	
1015	Cate	So that's . . yeah – it's going to be just like that (pointing to the diagram) . . OK well let's do it then. (Sue writes her prediction and Cate sets up for a new graph) . .	
[After a mechanical hitch with the first attempt they tried again.]			
1017	Cate	(Counting seconds) 1, 2, 3 . . Yeah . . Ready? . . Go! . . (Cate moves the wheel "up hill," stops, then "down hill") goes nnnyyaaa . . So that's – yeah! [It matched her prediction.]	

However, on some occasions the graph appeared counter to expectations, as with Tony and Jane's predictions for a ball rolling down an incline, hitting a rubber block, and rebounding. They predicted the displacement graph correctly, but Jane predicted the velocity graph incorrectly (line 1346 below).

1346	Jane	So it goes . . across and then it'll . . go up? – down . . like here it'll go for a short time and then it'll start again, so I reckon it will be there . . go there . . .and then it'll (= decelerate) (Tony: = decelerate) (Jane finishes her sketch) . . . . It's pretty weird.	Jane's predicted velocity graph 

After collecting their displacement data, the graph agreed with their prediction (line 1377 below, upper graph), but they hesitated (lines 1378 and 1379) when they saw the velocity curve (the lower graph on line 1377).

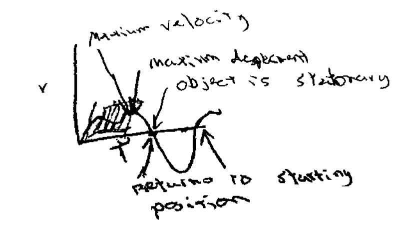
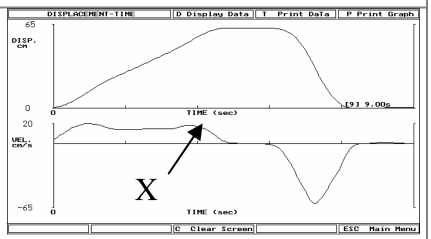
1377	Jane	So. Alright, well that's [graph] Number 1, OK? (Jane now displays the velocity-time graph, and both inspect it carefully.) . . .	
1378	Tony	Oh . . (Tony sees the velocity graph is not what they expect.)	
1379	Jane	Oh OK . . . Mmm . . We're almost there. (The displacement curve agrees with their prediction.)	
1380	Tony	Cause it – yeah (pointing to the graph)! We are [correct], except it goes to (Tony's hand draws downwards) . .	

Tony compared the predicted velocity graph (line 1346 above) with the actual velocity graph (line 1377, lower graph). When he realised the display graph correctly showed the ball returning with a negative velocity, he saw the error in his prediction and accepted the display graph.

5.1.1.4 Analysing, explaining and recording

During the first lesson the tasks involved creating a series of simple graphs that required descriptions rather than any analyses. Deeper analysis emerged in conversation when students compared these simple graphs using the graph overlay feature (to display multiple superimposed graphs), and also when they changed from the displacement screen to the velocity/acceleration screen. Students also created complex displacement graphs which they divided into simple sections for analysis, each section analysed according to both its shape and numerical data tables. These tables showed values of displacement, velocity and acceleration. Typically, students analysed and recorded explanations one section at a time, often swapping screens looking for confirmatory data.

In the following segment Mel and Hank were deep into one analysis, which was evident from the state of Hank's POE sketch shown on line 893 that follows. (Details of the sketch are indistinct and are not intended to be read.) Hank wanted to confirm that a point he marked on his velocity sketch represented the maximum displacement of the wheel.

893	Hank	Should I read it? . . "when the object has a maximum displacement" . . . is that the maximum displacement when it's at its peak? (Hank marks the peak of the velocity–time graph shown on the right as both "maximum velocity" and "maximum displacement.")	
894	Mel	Yeah it'd be ah . . just here (Mel touches Hank's notes) because – I'll just call it up. (He changes the display to show the displacement graph and corresponding velocity graph) . . . (= Right here). (Hank: = Here.) (Hank points to screen, Mel touches the peak of the velocity graph on the screen at X) . . because it's been gone for the velocity of a maximum and so it's just here.	

Mel changed the screen display to show the velocity graph (on line 894). He pointed out that the maximum displacement shown in the top graph corresponds to the point he touched on the lower graph (although, strictly, he was slightly in error). The arrows and shading in Hank's POE diagram show his technique of dividing a complex graph into simple sections for analysis.

A second example from Mel and Hank illustrates the section-by-section method of analysis and the screen-swapping techniques they used. For this Type II task the essence of their problem was to analyse the displacement graph shown in Figure 5.3 (the points A, B and C being added to assist the explanation) and predict the corresponding velocity and acceleration graphs.

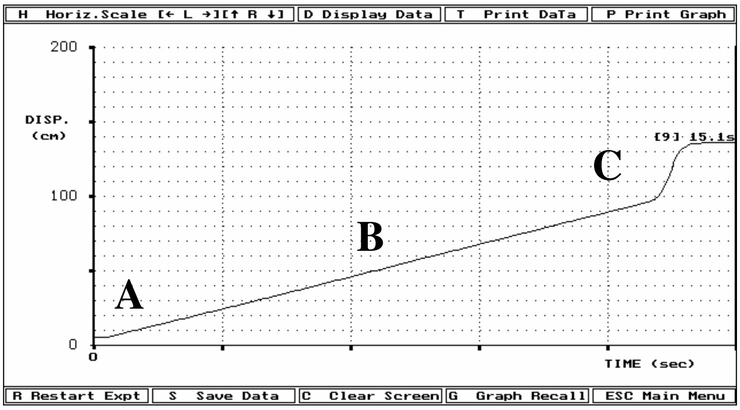


Figure 5.3. The displacement graph analysed by Mel and Hank.

Starting with the central section B they calculated the gradient using data from a screen showing data tables (not illustrated here). Next they analysed sections A and C, swapping back and forth between the data and displacement screens. Finally, they verified their calculations and conclusions by displaying the acceleration graph and calculating values from screen measurements. For Type II tasks the setting-up and observing stages of Figure 5.2 were bypassed.

The last two stages of analysing and explaining in Figure 5.2 are combined and expanded in Figure 5.4 (comparable to Figure 4.2 for thermal physics) to capture the practice of swapping between multiple screens for complex motion tasks.

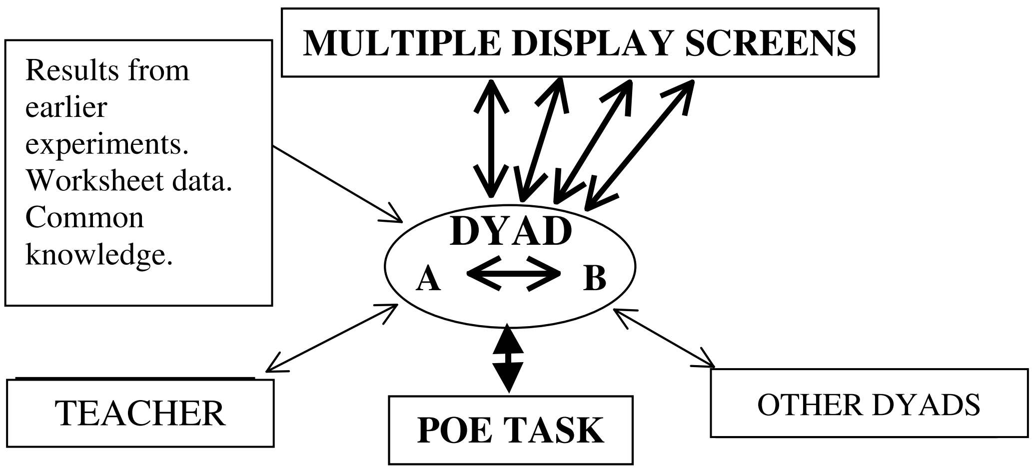


Figure 5.4. Network during the analysing and explaining stages for complex motion tasks.

Transcripts and teacher observations showed that students in the videotaped dyads shared their operation of the wheel, often depending on which student felt more confident modelling the wheel motion. Just as Mike often pursued his own agenda in thermal physics, so with kinematics Mel acted in advance of his partner on many occasions. The result was that Mel led Hank into explorations and dialogue he might otherwise not have experienced. Although the POE notes introduced velocity graphs in the second lesson, Mel experimented with velocity and acceleration graphs midway through the first lesson. Before the end of the lesson he conducted his own experiment to measure acceleration due to gravity, read results from the display of data tables, and speculated on sources of error, while Hank was the onlooker.

This section has identified the actors in the kinematics MBL and discussed examples of their patterns of interaction as illustrated in Figure 5.2. Type II tasks omitted the setting up and observing stages. The analysing and explaining stages for more complex tasks involving multiple screen displays are illustrated in Figure 5.4. Throughout all stages the medium of the computer display remained central to an interactive process by which students collaborated to construct knowledge.

The remainder of this chapter seeks to interpret the dialogic interactions between these actors. In each of a number of sections that follow, the discussion following the analysis presents one or more assertions, each illustrated by examples taken from the transcriptions. A summary of the 10 assertions made in this chapter appears in section 5.5.

5.2 THE ROLE OF THE DISPLAY IN STUDENTS' DIALOGUE

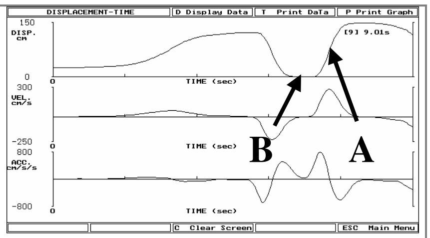
This analysis examines whether the videotaped dyads viewed the display as a graph in isolation from its origins, or as symbolic of the experiment. The principal sources of data used were the transcriptions of dialogue taken for the audiotapes, annotated with students' actions and expressions taken from the videotapes. The passages analysed included each instance when a new displacement graph was created, or velocity and acceleration graphs were displayed based on previously collected data. The unit for analysis was the turns of speech associated with the current task. This varied from one to seventy or so turns of speech. Students' written POE notes about meanings they attached to the display were also read in conjunction with the transcriptions.

5.2.1.1 Analysis

Of the 121 instances of students viewing a new graph, in 43 of these their dialogue or POE notes linked the display with the actual experiment or other physical concepts. On only five occasions students referred to the graphs as entities in their own right, in isolation from the experiment. In the remaining 73 instances students made no comments, neutral remarks such as “I don’t think it needs an explanation,” or equivocal comments such as “it’ll probably just go up slower.” The latter kind of remark could be construed as either a simple graphical observation (the line “going up”), or as a reference to the wheel (going “slower”). Because of the ease with which graphs were generated, students often repeated graphs without making comments, until they obtained a satisfactory graph.

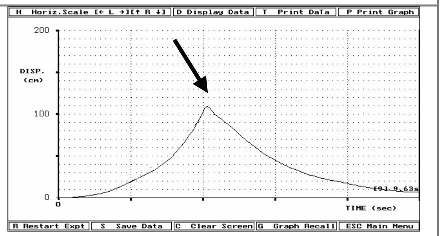
The analysis revealed six ways by which students linked the display to experiments or other conceptual models. Illustrative examples of each are presented below.

(1) *Students made a direct reference to the experiment.* One task required that students generate a graph of random motion for later analysis. When it came to the analysis, they had forgotten their original motion. They divided the graph into sections and proceeded to describe each section in turn. The dialogue between Mel and Hank in lines 310 and 311 below shows how they made the reverse connection from the displacement graph to the wheel’s movements on the bench.

<table>
<tr><td>310</td><td>Mel</td><td>It’s a constant fast movement – but no we are looking at displacement here (pointing to A on the top displacement graph). (He runs his hand along the bench quickly to imitate the motion.) That’s not accelerating or decelerating.</td><td>
</td></tr>
<tr><td>311</td><td>Hank</td><td>And the flat bit where it was . . you just didn’t move it [referring to point B].</td><td></td></tr>
</table>

Mel illustrated one section of the graph by running his hand along the bench. Hank directly said the flat section showed no movement of the wheel.

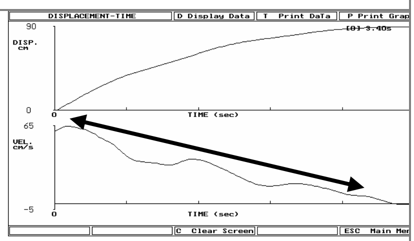
Jane simulated the motion of a ball rolling down an incline (line 1371 below). She ran the wheel along the bench, struck an imaginary rubber block, then reversed the wheel back along the bench.

1371	Jane	Right. Start off slowly, get fast, then hit that block and come back. Yep. Just like that . . .	
1374	Tony	(The graph is completed and both look at the screen.) Did you stop up here? (Tony touched the point of reversal on the bench.)	
1375	Jane	Aaar I just go – cause it bounces. (Jane's hand moves back and forth.)	

Tony saw that the peak of the displacement graph did not show a short horizontal section that he associated with stopping. He asked Jane (line 1374) if she stopped the wheel when the "ball" hit the block, whereupon Jane described her bouncing technique (line 1375).

When questioned by the teacher students readily explained complex graph shapes by making direct references to the movement of the wheel, or to the original problem simulated by the wheel movement.

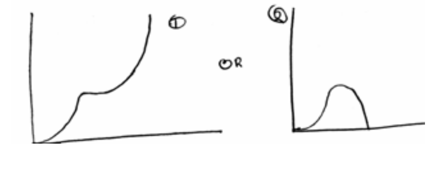
(2) *Students made non-verbal references to the experiment.* Mel had a new idea for creating an improved deceleration graph, which he tested independently to satisfy his curiosity. In the extract below he spoke as though to himself.

734	Mel	So if we actually . . do it again, . . . start off fast and go slower . . . (He starts the wheel and creates a graph of a fast velocity decreasing to zero.)	
[Hank asks Mel about the next experiment, but Mel wants to follow through with his idea and displays the velocity graph from his last trial.]			
738	Mel	I'll just have a look at this one . . . (He displays the deceleration graph he just made with its velocity graph. His response is immediate.) Right. So that is – right here (running his finger in line with the velocity graph line, which is fairly straight, as showed by the arrowed line).	

Though Mel made no direct reference to the experiment (line 738), it is evident that the graph confirmed his planned execution of the wheel movement on the bench.

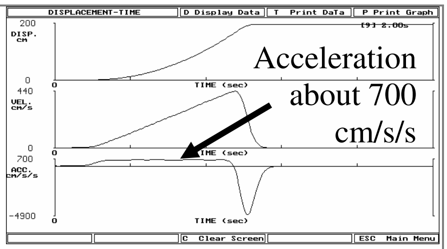
(3) *The unspoken link between graph and experiment became evident only in*

contemporaneous POE notations. Cate and Sue made two displacement graph predictions for a cricketer running two runs (shown below on line 797). For their first prediction the cricketer turned around 180^0 to make the second run; for the second prediction, the cricketer ran backwards for the second run. The experiment supported their second prediction.

797	Cate	Yeah it's alright! (Both smile and nod heads) . . I reckon that's pretty good. Yeah. (Both return to their notes. Cate's two predictions are shown on the right.)	

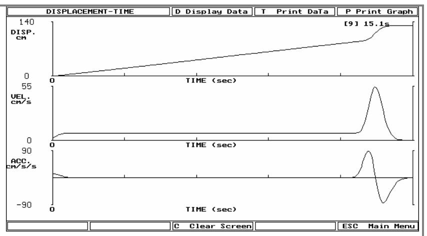
Line 797 shows that neither student actually voiced a connection to the experiment. However, their written POE notes revealed the association they made between graph and experiment. Cate wrote: "Observation 2 was where the wheel was not turned around and it was as if the cricketer didn't turn around." Sue wrote: "Our 2nd prediction was if the cricketer turned around and came back."

(4) *Students occasionally associated the display with other concepts apart from the experiment.* This instance occurred early in the first lesson after the teacher and Dyad A combined to create the displacement-time graph for a freely falling weight. After the teacher left Mel swapped screens to display the multiple graphs screen page, and immediately examined the acceleration graph. He recalled the value for acceleration due to gravity from the previous year, "980 cm per second [*sic*]" (line 211) and made an immediate comparison with the screen value of 700 $cm \cdot s^{-2}$.

211	Mel	(Looking back to the screen, mumbles) metres per second . . . 980 cm per second . . . that's interesting (pointing to screen) it should be like 980 cm a second . . . around 700 . . you've got a different . . error margin's like the . . ah . . . (Mel turns to Hank, who has almost re-wound the thread on the wheel) you've got different error margins like - like the wheel's (looks to the ceiling thinking) . . . umm . . . what do you call it?	

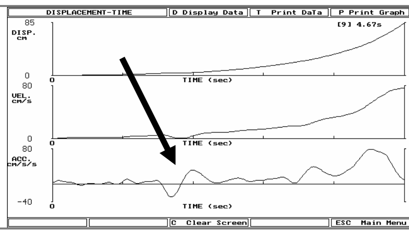
In the previous year Mel had used formulae to calculate the motion of falling objects. In these equations "g" was always taken as 980 $cm \cdot s^{-2}$. Now he was concerned that the screen data conflicted with his former view, and went on to suggest reasons for the discrepancy.

In the following instance Jane recognised in the velocity graph (shown in line 1694, middle graph) a "blip" not unlike that seen on a heart monitor display. She speculated (line 1694) that heart monitors may register the velocity of blood, because both the heart monitor and MBL wheel produced similar displays.

1694	Jane	Sshhht (hand moves up and down) . . I wonder . . what it is . . what it . . what one of those heart monitors takes? . . Like it's like that (Jane traces the screen velocity graph with her finger) . .	
1695	Tony	Is it – is it how fast the heart beats?	
1696	Jane	I don't know . .	
1697	Tony	Cause that'd be a velocity graph . .	
1698	Jane	Could be (smiling) . . There'd have to be something there, or like, that moves (hand rises and falls) . . so . . maybe it's the speed at which the blood flows along . .	

The above examples show the various ways in which students associated the display with the experiment or other physical concepts.

(5) *Students linked graph features with the characteristics of the MBL apparatus and the user.* Some features of the data and graphs were artefacts of the software, wheel sensor, or human operators. Generally, students recognised aberrations from these sources in their graphs and made allowance for them accordingly. Mel and Hank repeated the experiment just described. They tied a mass to two metres of string, wound the string around the wheel, then dropped the mass to unwind the wheel. The results were not ideal due to lack of practice with their technique. Consequently the acceleration graph appeared rather irregular to Mel when he viewed it (line 219).

219	Mel	Acceleration – that is one twisted acceleration graph (whistles).	
220	Hank	They say that it's . .	
221	Mel	I suppose . . around about how many times you'd wrap it around. [He thinks each undulation in the acceleration graph arrowed at right corresponds to wrapping the string round the wheel once.]	
222	Hank	Yeah.	
223	Mel	About how many times did you wrap it around the wheel?	

224	Hank	I don't know . . .	
225	Mel	We'll go onto the next one I suppose . . . (Mel touches screen to measure the wavy irregularities in the acceleration graph line). One two three [turns] . . . I reckon about 13. (Hank rewinds wheel and counts the turns, counting out aloud.)	
226	Hank	Ten.	
227	Mel	About ten [turns of thread around the wheel] (looking at the screen) – ah it's around ten – plus or minus – three (smiles) so I suppose each time it goes up it's kind of (Hank: = Yes) (= ?) . . .	

Mel and Hank tested their theory that the "waviness" of the acceleration graph was associated with the number of windings of the string round the wheel, and were satisfied this was a likely explanation of the irregular acceleration graph (lines 221 to 227).

Based on the teacher's observations and POE notes, the students generally accepted that wavering graphs for velocity and acceleration were caused by small irregularities in the way they pushed the wheel. They also explained irregular graphs in terms of the sensitivity of the MBL apparatus and human error.

(6) *Students applied mathematical treatments to the graph per se.* Five times students referred to the display purely as a mathematical entity. For two of these instances the students merely read data from numerical tables on the screen in response to specific POE questions. Only once did students apply themselves to what became a lengthy mathematical analysis of the display, without voicing any association to an external domain. Hank and Mel analysed a displacement graph (Task 8), from which they calculated values to draw the corresponding velocity graph. Other groups handled the same task qualitatively.

5.2.1.2 Discussion

> Assertion K1. Students viewed the display, almost exclusively, as representing the experimental phenomena or task problem. (The symbol "K1" stands for "Kinematics, Number 1 (assertion).")

The above examples show that students used the transformation capabilities of the computer to associate motion graphs with the wheel motions they represented. Students matched graph patterns with specific wheel movements, which in turn they discussed in terms of the original problems – cricketers running, persons cycling, and objects falling. The display helped them conceptualise directions of displacement, forward and reverse velocities, and positive and negative accelerations, as graphical representations. Students described how their hand-wheel movements translated to graphic displays, and the reverse process from graphic displays to the hand movements that formed them.

Students did not associate the graphs with a broad range of other conceptual models associated with the experiment, as was the case with thermal physics (see section 4.2.1.1). Kinematics, the study of pure motion, presents students with limited opportunities to draw on other key concepts in physics. Students were restricted in their conversation to the tasks at hand, simulating the movement of objects and people. The mechanical properties of the wheel and their own physiological limitations in moving the wheel smoothly were the exceptions. Neither did students apply any extended mathematical treatments to the graphs, with the one (simple) exception of Mel and Hank in Task 8. Advanced aspects of kinematics were hidden from these students, insofar as their mathematics was limited, and they had not yet studied rates of change, gradients, areas under curves or methods of calculus.

5.3 THE LEVEL OF STUDENT-DISPLAY INTERACTIONS

The relative frequencies of interactions between students and display is shown by the heavy and light arrows in Figures 5.2 and 5.4. This section now analyses the depth of interactions brought to the experiments by students, using the same criteria as for thermal physics (see section 4.3 and Table 4.1). Based on the work of Chin and Brown (2000) and Hogan (1999), the criteria in Table 4.1 categorise approaches students bring to their learning as ranging from shallow to deep. Surface level thinking typifies students whose prime motivation is to fulfil basis task requirements, and who lack motivation and initiative to build meaningful schema from a sequence of tasks. Students who take a deep approach reflect on the purposes of their activities, actively manipulate data, and integrate knowledge into new understandings.

5.3.1.1 Analysis

The analysis in this section was based on all of the dialogue over four days for Mel and Hank (Dyad A), over the first three days for Cate and Sue (Dyad B), and the fourth day for Tony and Jane (Dyad C). The transcripts of the videotapes were read for dialogue associated with students viewing the display, which accounted for 50% of the total lines of speech transcribed. Thus the analysis concentrated on student-student-display and teacher-student-display interactions. The dialogue was read and compared with the descriptors of surface and deep level approaches in Table 4.1. This table proved to contain a complete and sufficient set of descriptors to categorise all the dialogue in the kinematics analysis.

The total instances in shallow and deep categories are presented in Table 5.1, alongside students' names and academic ranks based on their assessed marks for the semester of the research. Totals for each day are reported separately. Comments are made later on the students underlined, because of some standout features in their approach to the tasks.

Table 5.1

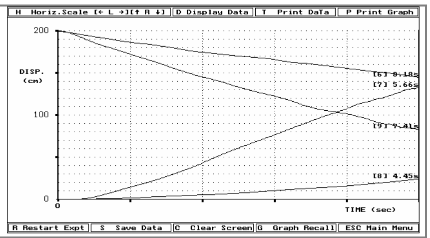
Frequencies of Surface and Deep Approach Expressions by Students Viewing the Kinematics Displays

Day	Dyad	Student ID	Student's academic rank (*n*=29)	Total instances of surface approach	Total instances of deep approach	Ratio of deep to surface approach
Day 1	A	<u>Mel</u>	4	63	<u>19</u>	<u>0.30</u>
		Hank	21	58	2	0.03
	B	Cate	9	76	7	0.09
		Sue	10	53	4	0.08
Day 2	A	Mel		61	13	0.21
		Hank		54	5	0.09
	B	Cate		62	15	0.24
		Sue		63	6	0.10
Day 3	A	Mel		85	37	0.44
		Hank		62	14	0.23
	B	<u>Cate</u>		72	<u>3</u>	<u>0.04</u>
		<u>Sue</u>		76	<u>3</u>	<u>0.04</u>
	A	<u>Mel</u>		45	<u>50</u>	<u>1.11</u>
		Hank		27	21	0.78
		Tony	1	82	37	0.45
		<u>Jane</u>	17	72	<u>55</u>	<u>0.76</u>

Surface and deep approach expressions formed a continuum and some subjective judgments were made to separate them, guided by the context of the dialogue and students' bodily actions. The meaning, and hence allocation, ascribed to a remark made by a student in deep thought may have differed for the same remark made by a student appearing tired and indifferent. The determining factor to qualify for the deep approach category was evidence that the students were probing beyond the surface and actively seeking to extend their understanding. The numbers and types of occurrences of all deep level expressions used by the students were:

- Judging a feature of the graph against expected criteria (100)
- Using the screen as a working diagram (43)
- Constructing or reconstructing explanations (38)
- Drawing comparisons with another graph or table of data (21)
- Explaining a cause-effect relationship (20)
- Making an extended calculation or estimation (15)
- Expressing wonderment, puzzlement or curiosity (14)
- Searching for an alternative data source to support an answer (12)
- Elaborating on a specific example (10)
- Self-evaluating ideas by expressing understanding, failure, impasse or value judgments (7)
- Eliciting further inquiry, such as proposing a further experiment to support a claim (4)
- Appealing to a graph to support a claim (4)
- Predicting, with reasons, how the graph would develop (3)

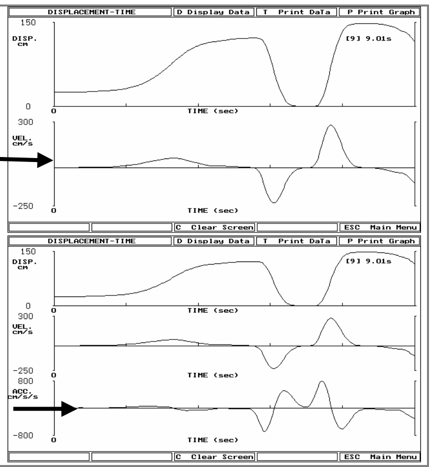
With reference to Table 5.1, no significance was attached to the fact that students mostly expressed surface approach comments, because these included necessary exchanges such as data values and simple questions or agreements. Surface comments were generally common for all groups on Day 1 for two reasons. Firstly, much of the discussion was procedural as students learned to set up and run experiments. Secondly, the initial tasks required simple wheel movements that gave students limited scope for in-depth explanations. This is illustrated by Mel's comment (line 86 below), after he and Hank completed four graphs for fast and slow, forward and reverse motion.

86	Mel	OK. I'll recall the other ones. (He overlays all three former graphs.) . . . (Mel starts to sketch graphs) . . . OK. I don't really think it needs an explanation do you?	

Mel and Hank, and Cate and Sue in Dyad B, spent little time discussing these graphs, but wrote clear POE explanations about their straightness and gradients.

The last column of Table 5.1 shows the ratio of deep to surface approach expressions. The higher this ratio, the more commonly the student took a deep level approach to tasks. Deep comments became progressively more frequent through to Day 4. This was due to the increasing complexity of the tasks, requiring students to synthesise concepts, make comparisons, and propose new types of wheel motion. Superimposed on this trend towards a higher ratio of deep level comments from Day 1 to Day 4, were some variations worthy of note. The names and data for these students are underlined in the table.

Mel (Dyad A) not only spoke more frequently than Hank, but when he did speak his expressions were twice as likely to be at a deep level (see Table 5.1). The transcripts and teacher observations painted a profile of Mel as a student who showed a particular originality in his approach to MBL tasks. Mel began to explore screen pages using the Main Menu just twenty minutes into the lesson on Day 1, and he proved adept at displaying and manipulating data from different screen displays, as shown in the extract that follows. Mel often spoke as if to himself rather than to Hank, saying "Interesting . . ." (line 153), followed by an extended period of thought.

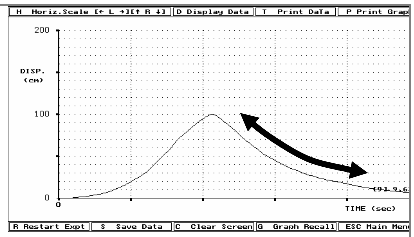
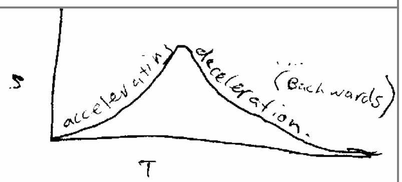
153	Mel	I kind of like analyse to see them all and ah . . (Mel turns to the velocity graph screen and recalls a deceleration graph.) Interesting. . . . . (He then recalls the random graph shown on the right.) There's ah velocity (He traces the curve with his finger) . . this graph is very well done heh! . . . . I think we can even get an acceleration graph (He returns to the Main Menu). Ooh that'd be good (displaying the acceleration graph on the right). Interesting. . .	

After completing tasks for Day 1, he used the final minutes of the lesson to manipulate the wheel and draw his initial "M" on the screen (line 326 below).

326	Mel	Twenty seconds. (Mel sets up a new graph and picks up wheel.) Pardon me . . . (He starts the graph and watches it grow.) . . . No! Ah! The wrong way! (He repeats the graph, and as they both watch the screen it is evident he is drawing his first name initial "M" in cursive script, with a few fancy wriggles, by rolling the wheel with his finger.) Hmm . . Is there any umm . . true displacement, like any direction on this? (Mel looks at the screen, then returns to the Main Menu) . . actually you couldn't could you. I mean you could have like a compass in here. (Mel rolls the wheel on the bench in a series of tight curves.) It would be interesting wouldn't it . . Probably no compass could (???).

Mel's play led him to speculate as to whether the computer could sense absolute (i.e., compass) direction, which underlined either his awareness of the vector nature of displacement or curiosity about the hardware interface. He took a metacognitive approach, self-evaluated ideas, and posed questions in the first person.

Mel recognised standard graph patterns that he used to construct and reconstruct explanations. In the following extract (line 946) Mel viewed the displacement graph of a wheel rolling forward from rest, rebounding from a wall, then slowing to a stop. In line 946 he puzzled over the concave shape of the return half, as to whether it represented acceleration (which it did), or deceleration.

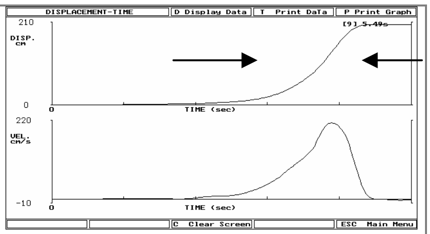
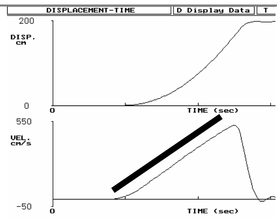
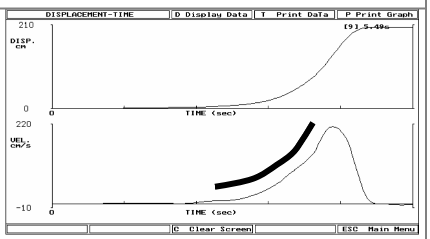
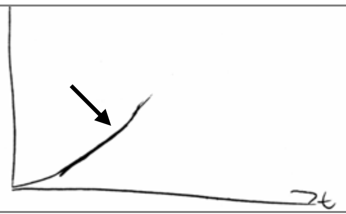
946	Mel	Great. . . . It's funny there, but if something's like – going forward (rolling the wheel), and then it goes backwards, if it's slowing down like that would you call it acceleration or deceleration? – if it's going backwards? . .	
947	Hank	I think I'd still call it deceleration	
948	Mel	Yeah.	
949	Hank	if it's going backwards.	
950	Mel	Right but – on the graph it's got the same type of curve as in acceleration . . . (Mel's POE observation on the right, with 'backwards' later added to 'deceleration.'.) OK.	

Hank repeated the commonly held view (lines 947 and 949) that deceleration is associated with negative displacement, or a descending displacement graph. Mel countered by appealing to a graph pattern from two lessons previously. He connected acceleration not with the direction of the curve (descending), but with its shape (concave upwards). He amended his POE note to read "deceleration (backwards)," which he correctly equated with acceleration.

Another characteristic of Mel was his inclination to search for alternative approaches to confirm or disconfirm his ideas. Three times he planned and conducted successful experiments to test conjectures about acceleration graphs.

Jane (Dyad C) also expressed a high proportion of deep level comments in comparison with her partner Tony (see Table 5.1). Her self-confidence was evident yet unexpected, because four weeks earlier she was unsure whether she could cope with the demands of the physics course. For these experiments she partnered Tony at the teacher's request to make up a mixed sex dyad. Though Tony was more gifted academically he often asked Jane her opinion and accepted her suggestions.

Jane noticed the significance of finer details in graphs, and worried when they failed to match her expectations. Task 7 required the students to translate the displacement graph for a falling mass into velocity and acceleration graphs. Unbeknown to Jane and Tony, the graph they analysed originated from a hand-simulated example of a falling mass made by Dyad B, and not that of an actual weight. When she saw the velocity graph (line 1555, lower graph) Jane immediately noticed an irregularity (line 1556). She explained to Tony (line 1558) that the shape of the line should be straight and not curved.

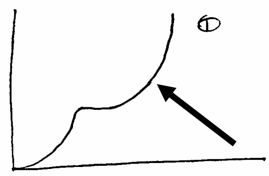
1555	Tony	(Jane displays the displacement and velocity curves) . . . (Jane: Uh oh) . . Yeah (Tony touches the screen in the section between the arrows). We just need that bit there (shown between the arrows), which is – you know . .	
1556	Jane	It's not the same (Jane shakes her head sideways. She realises the velocity graph section should be straight, as seen in an accurate graph on the right.) . .	
1557	Tony	Yeah it is.	
1558	Jane	It should to from there – to there – straight. (Jane touches the rising part of the velocity curve.)	
1559	Tony	Well then it's just the . . the difference . . of the . .	
1560	Jane	(Jane looks very sceptical) . . .	
1561	Tony	It's still pretty straight (touching the screen) a little bit like	
1562	Jane	that part there. (Jane touches a short section that is in fact straight) . . Oh we'll say that's right . . . . [On her POE sketch of the velocity curve Jane drew a thicker straight line in one section of the rising curve.]	

Though Jane appeared to concede to Tony's viewpoint (line 1561), she drew a thick straight line on her POE sketch of the graph (shown on line 1562) to show that she understood what the model graph template should be. Jane correctly criticised the acceleration graph similarly. She frequently used the screen as a working diagram and constructed explanations based on graph features twice as often as Tony.

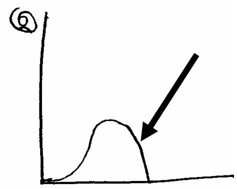
Cate and Sue (Dyad B) also operated at a level not markedly different to Dyad A during the first two days and for the first half of Day 3 (see Table 5.1). For example, on Day 2 Cate and Sue discussed at length (78 turns of speech) the cricketer problem:

> Task 4.2: A cricket batsman hits the ball and scores two runs. Study the motion of the batsman.

After using the wheel to simulate the task, they meditated on the screen display (line 773 below) for a considerable time, absorbing its message.

773	Cate	Yeah . . OK OK Go! (She runs the wheel forward and stops, turns the wheel around, runs back to start, and stops. Both then look at the screen.) Is that right? Yes! We got that! (Sue nods approval. Both think about the screen display for 12 seconds. Sue has no expression. Then she nods, and turns to Cate, meditating) . . . . Yeah . . . . . OK. That's interesting . . . . except . .	 Cate's copy of the display

The display matched one of their two predictions. Sue then wondered why the second part of the curve rose, (line 773, arrow) and realised this was because they had turned the wheel around. As she explained (line 774), if the wheel was run backwards the curve would descend (line 774, arrow).

774	Sue	Oh that's because when you go like that (drawing a downward curve) [arrowed right] . . . that's . . . that would be if . . you kept on going backwards (she pretends to run backwards) and ran back (pointing over her shoulder), wouldn't it? Is that right?	
775	Cate	Yep. (Sue: = and then) (= If you just stopped) and then went like that. (She bends her shoulders backwards.) (Sue: = Yep) (= Yep). That'd be (as she runs the wheel forward, stops, then returns with the wheel running backwards) . . (Sue: = Yeah.) (= Yeah.) So you could . .	Cate's copy of the same experiment, this time not reversing the wheel.

In line 775 Cate supported Sue's explanation, and they proceeded to repeat the experiment, this time not reversing the wheel 180 ^{0} to simulate the batsman running backwards for the second run. Cate and Sue flourished when they had successes. They continued to discuss this same experiment in depth for another 65 turns of speech.

However, halfway through Day 3 Cate and Sue met with a series of situations that affected their progress. Their number of deep approach comments dropped dramatically (see Table 5.1). While their problems will be discussed more fully in a following section (5.4.5.1), briefly they were these. The girls misread Task 5 and consequently did not progress through the stages that associated patterns of simple displacement graphs with their corresponding velocity graphs. They also failed to master the software procedure for recalling graphs that they had saved in previous lessons. In this extract taken from Day 3, Sue tried to recall graphs from Day 1, but had forgotten the graph-labelling system she used (line 1142).

1142	Sue	Yep . . OK. It has to be after that. . . I don't think we saved some of them . . cause we got three after that . . Oooh dear . . (recalling Task 4.1 again). So that's that one. (Recalls Task 4.5) . . What's that one? (Sue checks her notes.) I think it's the cricket one . . . (Sue recalls Task 4.1 again.). . . It's cool Cate. We've lost heaps of them [i.e., graphs. Actually some that she is looking for are saved, but Sue cannot locate them.]
1143	Cate	Yeah OK. Let's do them again.
1144	Sue	Oh can you still walk this thing [move the wheel] ? OK.
1145	Cate	Oh yeah.
1146	Sue	This one [Task 4.3: Car starting at green light].
1147	Cate	It's for idiots. (Cate is becoming frustrated.)
1148	Sue	Let's see if we're ready. . OK.
1149	Cate	Oh I've lost it before it starts . . (Cate does some stretching exercises and yawns profusely.)

The girls had no plan of approach, and shortly thereafter they bypassed the task. Because of not laying a foundation with Task 5, they were unable to cope with later tasks, thus adding to their frustration. To compound their problems, both girls arrived for the lesson extremely tired. At the same time as Dyad A and Dyad C were holding deep and extended discussions, Cate and Sue lost their direction and motivation. The teacher considers that this period for Cate and Sue was an aberration, contrasting with their usual classroom activities.

As a further measure of the depth of their thinking, all students' POE notes were read and assessed for the quality of their explanations. During the first two days the large majority of students completed thoughtful explanations for the shapes of their graphs. On Days 3 and 4 the quantity and quality of written explanations progressively decreased, and issues relating to this will be taken up later (section 5.4.5). A few individuals made sparse notes "because [they] didn't think they would be collected" (AS2140300) and others said they did not know what to write or felt they were writing the same things repeatedly. POE explanations reflected a wide range of depth of thinking. In writing about the shapes of displacement-time graphs for acceleration and deceleration, all students noted that they were curved, but only one half of the students elaborated on this simple observation. Nevertheless the lack of notes gave no direct measure of the depth of thinking students brought to the tasks.

Six of the twelve student groups were interviewed, and five of these were able to give lucid accounts of the meaning of motion graphs they had completed. Members of Group G and two or three other individuals lost their focus on the third day. Matthew (Group G) explained: "I like . . . was kind of bored because it was getting real repetitive like doing the same task and stuff." (AS1140300)

5.3.1.2 Discussion

> Assertion K2 During student-display interactions, while students' activities ranged from fulfilling basic requirements to deep level cognitive processing, the dyads completed the majority of tasks at a deep level of mental engagement.

This section analysed the depth of students' processing of ideas while they interacted with each other and the display. The primary analysis was based on characteristics adapted from Chin and Brown (2000) (Table 4.1), using transcriptions of dialogue and student interviews. To reiterate, students who took a shallow approach to learning met the basic requirements of the task without reflection as to its purpose, and failed to associate details with other meaningful schemata. Those who took a deep approach were intrinsically motivated, and actively manipulated data with a focus on understanding and integrating knowledge.

The frequency of students' expressions at a deep level varied according to individual learning styles: Mike and Jane excelled over their partners when it came to expressions of deeper thought. The students in Dyad B on Day 3 accidentally bypassed a key task, and hence failed to understand some basic graph patterns. This constrained them in their depth of approach to some later tasks. In the main laboratory students showed evidence of deep level thinking in their POE explanations, with the exception of Group G and two or three other individuals. The teacher had little more than superficial interaction with these students, due to the large class size, an issue to be addressed in section 5.4.5. Nevertheless, the POE notes of all the videotaped students showed they probed beyond the surface and actively sought to extend their understanding of the tasks.

> Assertion K3. Students' deep approach to learning was supported by the enduring nature of the display.

Students came to the laboratory having little familiarity with displacement graphs, minimal experience with velocity graphs, and none at all with acceleration graphs. For introductory tasks the displacement graph display became the de facto experimental artefact, a record of the task simulation frozen in time. Velocity and acceleration graphs were secondary graphs, derived from displacement data. The derived graphs displayed information even further removed from intuitive understanding than the primary data. More difficult tasks required analysis of the derived graphs. Consequently the interpretation of graphs, and relationships between graphs and task problems, required extended references to the display. Assertion K3 recognises that the wealth of screen information took a considerable time to extract. Table 5.1 listed a total of 291 instances of deep approach expressions by the videotaped students as they viewed the display. Dialogue during their actual viewing accounted for 50% of the total lines of speech during experiments. Furthermore, videotapes showed that students frequently spent extended time silently meditating on the display, particularly on the multiple graphs. Assertion K3 contends that because the display was accessible over an extended period of time, they were able to probe beyond a superficial assessment of data and extract deeper meanings.

It is true that Cate and Sue used their POE sketches of the display (and not the original screen) for much of their analysis, but this was not the norm. This dyad met with difficulties in recalling graphs, which reduced them to analysing their sketches.

There was no basis to make a direct association between students' frequency of deep thinking approaches and their academic ranks. Dyad C was a case in point, in which Jane (17th in academic ranking) exceeded Tony (1st ranking) in expressions of deep level thinking. Other important influences on the depth of students' thinking, such as class size and teacher interaction with dyads, will be addressed in section 5.4.5.

5.4 STUDENT UNDERSTANDINGS MEDIATED BY THE DISPLAY

In Chapter 4: Learning About Thermal Physics in an MBL, section 4.4 began with a summary from the literature of how MBL methods, experiences and social environment enhanced student understandings of experiments and graphic data. That summary may equally preface this section on learning kinematics in an MBL.

The literature also documented difficulties commonly made by students in relating graph features to experimental phenomena (McDermott, Rosenquist, & van Zee, 1987). They were: (a) confusing the meanings of height and slope of a line; (b) confusion between the picture of a moving object, and its displacement and velocity graphs; (c) interpreting curved graphs which combine changes in height with changes in slope; (d) translating between displacement, velocity and acceleration graphs; and (e) matching the information in a written passage to a graphical representation. A number of these became apparent in the present study.

The following analysis examines four aspects of how student-student-display interactions mediate student understanding of introductory kinematics. They are: (a) how students critically evaluated the display graphs, (b) how they collaborated to create and interpret graphs, (c) the teacher's mediating role, and (d) student limitations and delimitations in learning about kinematics in the MBL.

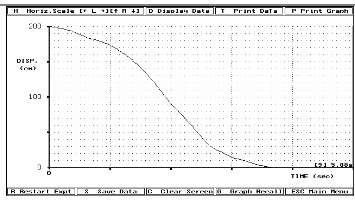
5.4.1 Students' assessment of graphic data

This section examines how critically or otherwise students viewed the display. It analyses to what extent and by what criteria they engineered its creation, how consistent it was with their knowledge of the subject matter, what error tolerances they were prepared to accept, and their basis for accepting the display as an accurate portrayal of the data. The principal sources of data for analysis were the transcripts of audiotapes, annotated with information from the videotapes. The students' POE notes, semi-structured interview transcripts and teacher diary notes were used as supporting data. The analysis only included dialogue that transpired while students watched the display.

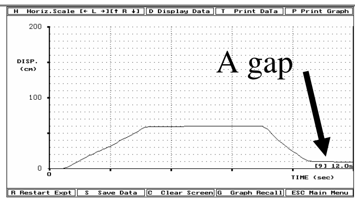
5.4.1.1 Analysis

For all but two of the Type I experiments (those collecting primary displacement data), all students collected data by manoeuvring the wheel in accord with a plan to simulate a problem. The exceptions were measuring the rates of fall of a mass in air, and a magnet through a copper pipe. The quality of data accepted for analysis was subject to the critical acceptance of the students.

In this first instance, Cate and Sue tried to obtain a smooth graph for deceleration, but ran out of bench space. In line 283 Cate pointed to the last part of the graph showing that she slowed down. The simplicity of repeating the data collection made it easy for Sue to suggest they try again (line 286).

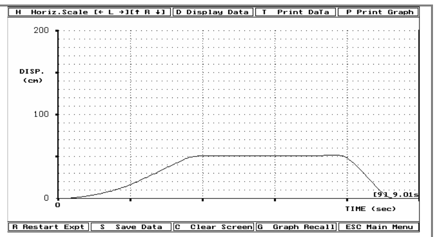
282	Sue	Ready? Go. (Cate moves the wheel backwards. They view the screen.) . . .	
283	Cate	Ssssshhh (She traces the graph line with her finger in the air). Oh see I got slower down there [at the end]. So shall I do it again?	
284	Sue	Yeah cause you ran out of (running her hand back and forth to show lack of bench space).	
285	Cate	Yeah. So shall I do it again?	
286	Sue	If you want. We can just keep that one and do another one. Cause we can do a few if you want.	

Features of graphs that attracted criticism were often very refined. The following day Cate and Sue were modelling a person walking forward for four seconds, stopping for four seconds, then returning to the starting position in two seconds. At their second attempt Cate noticed that the last part of the line fell just short of the origin. "I have to make it look good" (line 602).

601	Sue	OK? Ready, go! (Cate rolls the wheel and both watch the screen.)	
602	Cate	1 2 3 4 1 (= 2 3 4 1 2) (Sue = 2 3 4 1 2) [seconds]. (Sue claps.) [The wheel did not quite return to the start position, and Cate notices this.] Ah see I have to make it make it look good.	
603	Sue	It is too [an acceptable graph].	

604	Cate	Yeah but I have to make a mark like that, OK (drawing a starting line on the bench)? Like start from the end (holding the wheel at the edge of the bench) so we go 1 2 3 4 [seconds] (quickly rolling the wheel forward) and then stop there (touching the bench; Sue nods) and then go 1 2 [seconds] and I have to come back here (touching the starting edge of the bench) in 2 seconds (??).	

Though Sue reassured Cate that the graph was acceptable (line 603), Cate drew a starting line on the bench and practised getting it right, counting out the seconds for each stage. They restarted the graph (line 607).

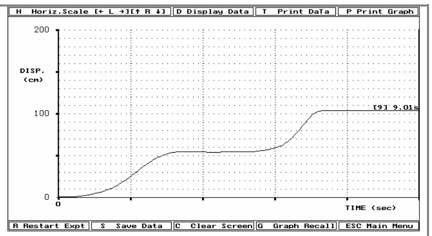
607	Sue	OK. (She sets up a repeat graph) . . . Ready? Yep. Go. (As the wheel rolls, both alternate between viewing the screen and the wheel.) 1 2 3 4 1 2 3 4 1 2 [seconds]. (Sue claps again.)	

Even as Cate copied the graph she was critical of its height (line 616), which did not fill the screen. However, she judged that the graph was acceptable (line 618).

616	Cate	(She copies the sketch.) It's not as sharp like not as high (raising her hand upwards, viewing the screen graph).
617	Sue	Yep.
618	Cate	But that's alright . . . . OK.

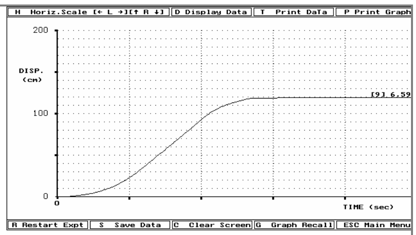
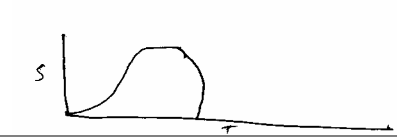
This account also illustrated how students planned, executed, judged and repeated experiments.

After gaining some experience with graph predictions, students learned what features to look for and could state clearly why a graph was acceptable. In the lesson following the previous example, Cate and Sue went through a period of sorting out in their own minds issues involving forward and reverse motion. Finally Cate and Sue modelled a variation of the previous graph (line 607), and in this case the cyclist did not return to the origin after a pause, but continued in the forward direction.

1017	Cate	Ready? . . Go . . (Cate moves wheel ‘up hill’, stops, then ‘down the other side of the hill’) goes nnnyyaaa . . So that’s – yeah (Cate sits and Sue starts to write her observation notes) . . and we can say it went like that because it’s going in a positive direction all the time.	

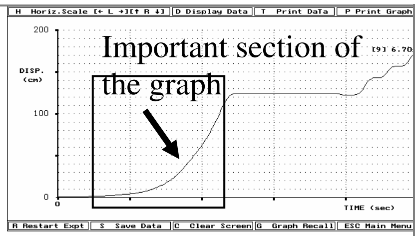
Cate reached a level of confidence with graph prediction such that she could look at a graph and say ‘thus and so is why that graph is good,’ which is effectively what she said in line 1017.

On the other hand, Mel intentionally accepted some graphs even though they were contrary to his predictions. Twice he re-evaluated his predictions in the light of truths made evident in the display. Here Hank and Mel simulated a car accelerating from rest, continuing forward at steady speed, then stopping.

427	Hank	You’re ready? 3 2 1 [seconds count down to start]. (Mel runs the wheel, then both view the screen for 3 seconds.) Right!	
428	Hank	Did you decelerate?	
429	Mel	Yes (meditating) . . Of course it would be that wouldn’t it [i.e., the graph shape, contrasting with his prediction shown on the right.]	

Hank asked (line 428) if Mel had decelerated, apparently because he saw the graph line did not descend at the finish. Both students had confused displacement with velocity graphs. Before Mel rejected the graph, at variance with his predicted sketch (line 429), he gave it dutiful thought and accepted its message – “Of course it would be that wouldn’t it!” Mel made the same type of error in the next lesson: “Damn it (he laughs) I’ve been doing too many velocity-time graphs. What was I thinking!” (line 932, not shown).

Students assessed graphs according to their needs at the time. As she gained experience Cate learned to analyse a small section of a graph and disregard the rest. On Day 1 she and Sue worked hard at getting an acceleration graph to fill the screen. Then on Day 3 they repeated the graph.

1267	Cate	Ready, go! [A good acceleration resulted. After the wheel reached the end of its 'run', it stopped for a while, then Cate hand-rolled the wheel a bit further] . . So we're going to have to look just at the start part [i.e., the section shown inside the box].	

Cate was satisfied with analysing one section of the graph (end of line 1267). A graph that Cate would have rejected on Day 1 she judged to be adequate on Day 3.

Even a random graph had to meet Mel and Hank's criteria. They repeated their first attempt after Mel said "I think we need like 15 seconds because you don't get enough time to kind of move it to its full limits," and Hank replied "Don't make it too hard, you've got to analyse this later" (lines 140 and 141, not shown).

Students came to the MBL with minimal experience at drawing pencil-on-paper displacement graphs. "We did a bit of graphing last year, but not this sort of graphing. Not really analysing graphs" (Tony, AS3020300). Most of the background knowledge students drew on to evaluate the display came from knowledge accumulated during prior experiments. Feedback from earlier graphs led to improved criticism of later graphs.

Sue: And then we realised after we got the observation, we thought oh, it's going to be the same as the first one, so it goes down again . .

Teacher: So there were occasions when you did one experiment, your mind then was brought back to an earlier one, to make a comparison.

Sue: = Yeah (Cate: = Yeah) (AS2020300)

A print-out of all of the graphs saved during the four days shows that every group consistently produced graphs that met the criteria for the tasks. When Chandra was concerned about irregularities in a graph he approached the teacher:

Chandra: Sir what sort of errors do you call these? Graphing errors or what?

Teacher: Mechanical errors in the wheel.

Chandra: Oh mechanical errors.

Teacher: Yes. That should be a nice smooth line.

Chandra: OK, and what . .

Teacher: and – and also – errors in how smoothly you move something. Let's come back to your table [i.e., to obtain a better result].

(AT030300)

Groups in the main laboratory frequently compared graph shapes, but far less so for the two groups being videotaped due to their being in isolated rooms.

For Type II tasks velocity and acceleration graphs were derived from primary displacement data. However, an apparently smooth displacement curve could produce a slightly wavering velocity curve, and an even more wavering acceleration curve. Only data from a non-human source, such as a falling weight or a magnet falling inside a copper tube, yielded smooth data for derived graphs. Consequently, when students viewed their displacement data as velocity or acceleration graphs, they were often surprised that the curves were not smooth. The centre graph in Figure 5.5 below shows that Carl expected a straight (constant) velocity line, but the actual line shown beneath it, copied from the screen, was wavy.

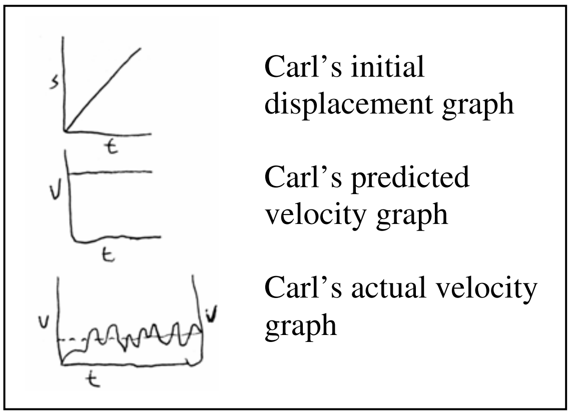


Figure 5.5. Predicted and actual graphs sometimes differed.

Even the acceleration curve for a falling weight may waver depending on the care taken in obtaining data. Mel correctly attributed one graphing error to a mechanical source in the wheel. Many POE explanations of these sketches showed that students attributed the "waviness" to human irregularities in pushing the wheel. In the third of the sketches above, Carl drew a straight dotted horizontal line on his copy of the velocity graph display, and wrote beneath it "All my predictions were all right apart from bumps due to human error."

5.4.1.2 Discussion

Assertion K4. Students critically evaluated the appearance of the graphic display.

Students proved to be exacting in what they were prepared to accept, rejecting poor graphs, which was not burdensome considering the ease of repeating experiments. The criteria for accepting a graph included its "filling the screen," portraying the group's interpretation of the task (or their self-corrected interpretation), and displaying features consistent with earlier graphs based on similar movements. The critical evaluation of the display was a developmental process because many of the graph shapes were not intuitive, nor had the students much background with motion graphs on which to draw. Students allowed for human error, specially when interpreting velocity and acceleration graphs. Though Assertion K4 is the same as that made for thermal physics (section 4.4.1), the underlying differences in collecting and evaluating thermal and kinetic data will be addressed in the Chapter 6.

5.4.2 Dyadic discourse and graph interpretation

In this section a variety of lengthy exchanges and brief excerpts has been selected to illustrate collaborative activities within and between dyads: the range of techniques and activities they devised, instances of constructing new concepts, how the display served as a referent source of information, how they drew on prior knowledge and resources, as well as document difficulties students had with interpreting kinematics graphs.

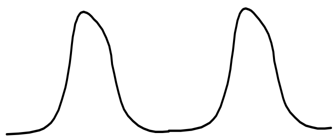
The data analysed were the annotated transcripts of student audiotapes and POE notes written during the videotaped lessons. Contemporaneous speech, actions, viewing and writing provided an insight to students' thought processes. The unit of analysis ranged from one to multiple turns of speech that completed an action, led to a conclusion, or was an isolated question-answer exchange. The only dialogue excluded involved that of teacher participation. Student tasks were of two types: Type I that required an experiment to capture data, and Type II that processed data from a previous experiment. For the former, students spent a considerable time interpreting the task, predicting, and setting up the experiment, before the display showed a graph. For the latter, students recalled to the screen a previous displacement graph, and from this determined their predictions for velocity and acceleration graphs.

5.4.2.1 Analysis

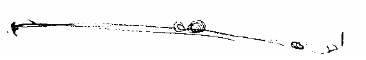
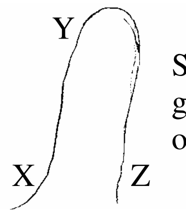
Prior to this lengthy vignette, Cate and Sue practised drawing displacement-time curves for simple situations, but had not examined velocity-time curves.

> A cricket batsman hits the ball and scores two runs. Study the motion of the batsman.

Cate intended to draw the required displacement graph, but drew in the air with her finger a velocity graph instead, the first "hump" being the first run, the second hump the return run. [Explanation: A batsman runs from one end of a straight 20 metre pitch to the far end, then returns, to make "two runs."]

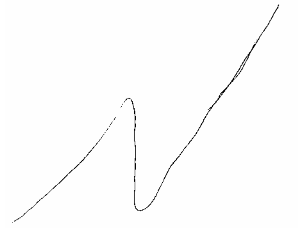
703	Cate	Oh OK. So that would be like (her hand draws a curve upwards to a stop then back to the original horizontal level) that would be the first half [first run] (then her hand repeats the same curve again) and the second one [run] would be like that as well, so it would be (drawing a double-humped curve in the air again) . .	
704	Sue	Yeah, cause he has to accelerate . . and he can't accelerate to turn around (twisting her arm behind her back) with the bat	
705	Cate	Yeah (her finger high in air).	
706	Sue	and then stand up again (and does a running motion with her arms).	

Sue agreed (line 704 above), saying that the flat part between the humps showed no "acceleration," allowing him to turn around. To supplement her graph Cate sketched the ends of the cricket pitch on the bench top (line 707, X and Z on the diagram).

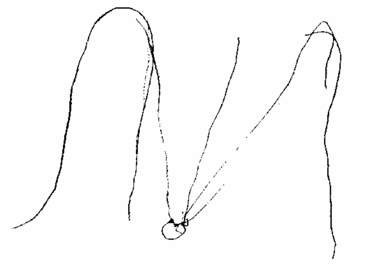
707	Cate	Hang on but what about if he went like that (drawing one hump in the air) – yeah, accelerating (hand curves up), and then he's in the middle like that – and then he goes like (turns to show by drawing on the paper) . . he goes – these are the two wickets [i.e., drawing ends X and Z on her diagram on the right] – two things you know whatever you call them [i.e., wickets] (Sue nods with a smile) and he has to run from here to here [X to Z]. He will accelerate – I think he'll be accelerating [X-Y] and then he will start to decelerate in there [Y-Z].	
708	Sue	Oh so basically because they are turning around (she turns her shoulders around) (= they sort of . .) (Cate: = Yeah but . .) no they decelerate until there (touching Cate's diagram of the pitch at Z).	
709	Cate	Yeah OK. So they go like this (Cate sketches one hump for one run, corresponding to the pitch sketch).	 Sketch of graph for one run

Both Sue and Cate imitated the batsman's movements. Cate drew (line 709, diagram) a velocity graph instead of displacement graph. Sue then gesticulated to describe the second run (lines 712, 714). She drew another sketch, adding a final upswept line to the hump, to represent the second run (line 718, sketch).

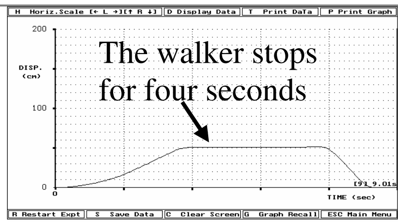
712	Sue	And on the way back he is just accelerating all the way (sweeping her hand upwards in a large arc).	
713	Cate	Yeah.	
714	Sue	Oooh (arms motion as if running) – cause they don't slow down they go fast.	
715	Cate	Yeah.	
716	Assistant	Specially if the fielder has the ball.	
717	Sue	Yes!	

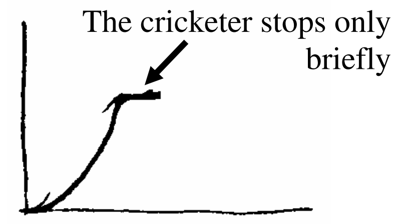
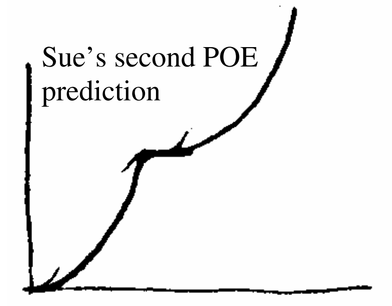
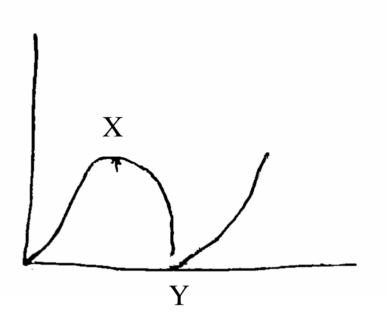
718	Cate	(She sketches the ‘displacement’ graph.) OK is that right do you reckon? . . .	

Their prediction (line 718) changed the “double hump” to show the batsman did not slow down on the return run. The final upwards sweep of their sketch seemed to represent displacement, making a hybrid velocity-displacement curve. Cate then sketched a large velocity graph (line 727, graph), vacillated, and returned to her double hump idea.

727	Cate	OK. So he goes like. . he accelerates, and then like stops accelerating about here, and then starts decelerating. (Meanwhile Sue turns to her sketched graph.) That would go (draws first hump, then a circle for the far wicket) like that, except it would be (then draws a second hump for the return run).	

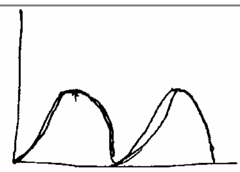
As both girls drew these graphs for their POE predictions, Sue had an insight. She recalled the previous task (“A person walks forward for four seconds, stops for four seconds, then returns to the start in two seconds,” line 742 below). Sue realised that when the walker stopped the graph did not descend, which led her to correct the batsman’s graph. She changed from a velocity to a (correct) displacement graph concept, which Cate also took up. With an eye to detail, Sue pointed out (line 744) that the cricketer stopped only briefly compared to the person walking.

742	Sue	It could just (draws upward curve in the air) . . maybe it just stops like the walking one (Cate: = Yeah) . . . cause you know how (Cate: = it just stops.) (draws in air a rise, then a horizontal line).	
743	Cate	He stops. (Her hand rises and stops.)	

744	Sue	It's just (clicking fingers to show a short period of time) that the cricketer doesn't stop for as long does he, like (drawing in the air what she later sketches in one of her predictions) he goes wooop – wrrrrmm.	
745	Cate	Like.	
746	Sue	Like it might have a little (horizontal bit) drawn.	
747	Cate	Like.	
748	Sue	Oh OK then I think he starts going up and then (Cate: = starts to curve in a bit) (Sue sketches)	
749	Cate	(= hang on). If he's going to stop – OK – then he accelerates like that, and then he stops and turns around (touching X) . . and then he goes . . . back – ah he'd go like this (returning to Y to begin the return run). . like that . . (showing her sketch to Sue) you know what I mean? . . Would he go like that? . . . Decelerating that way (pointing to right).	

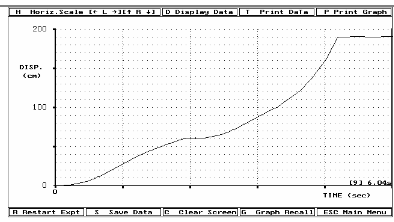
Sue continued the sketch upwards (line 748, last part of graph) to picture the cricketer making the return run. However, Cate (line 749) clung to her sketch of line 718. Cate accepted that the cricketer stopped at X (line 749, graph sketch), but somehow she brought him back to Y to begin his second run. Cate also said "he stops and turns around" – he rotated 180^0 – for the second run. Both Cate and Sue visualised him running turning his body 180^0 to complete the second run; hence they both ended their displacement graphs rising instead of falling.

Since Cate and Sue failed to agree on parts of their graphs, they made separate predictions (line 755).

755	Cate	We'll make two predictions. (Sue: = OK) . . One (drawing her first prediction on the right) . . (???) turn around the other way, it goes . . . . [Cate's first prediction shows the cricketer stops at the end of his second run. Also, Sue's first prediction shows the cricketer not slowing for his second run.]	 
756	Sue	Cause when we did the other one [i.e., the person walking] we had to slow down to stop (Cate: = Yep) and the graph didn't go wwrrrr (drawing a downward line in air) it just sort of flattened off (drawing a horizontal line in air).	
757	Cate	Oh yeah.	
758	Sue	But I don't know (a throw-away line as she shrugs and writes).	
759	Cate	(Mumbles as she sketches her second prediction) (???) again – Oh OK I see what you mean . . . Yeah . . . . . Like that you mean (showing her second prediction to Sue, who draws an identical sketch).	

In line 756 Sue once again tried to reason with Cate that her graph was incorrect. Finally Cate drew her final prediction (line 759, graph sketch), which was a step closer to the correct displacement graph.

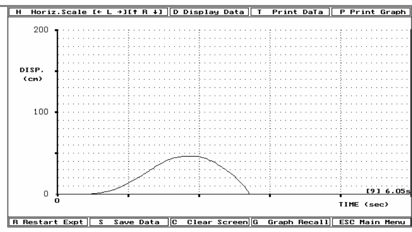
The girls then simulated the cricketer using the wheel, and created a graph which confirmed their second prediction. Both paid particular attention to the second half of the graph, a rising curve (line 773). In lines 774 and 775 both agreed that if the wheel had <u>not</u> been rotated 180^0 the graph would have fallen.

773	Cate	Yeah . . OK OK Go! (Sue runs the wheel forward, stops, turns the wheel around and runs back to start, then stops. Both look at the screen.) Is that right? Yes! We got that! (Sue nods her approval. Both ponder the screen display for 12 seconds, Sue has no expression. Then she nods, and turns to Cate, meditating.) . . . . Yeah . . . . . OK That's interesting . . . . except.	 Likeness of their graph, which was not saved.

774	Sue	Oh that's because when you go like that (drawing a downward curve) . . . that would be if . . you kept on going backwards (pretending to run backwards, pointing over her shoulder), wouldn't it? Is that right?	
775	Cate	Yep. (Sue: = and then) (= If you just stopped) and then went like that (bending her shoulders backwards) (Sue: = Yep) (= Yep). That'd be (running the wheel forward, stops, then returns with wheel running backwards) (Sue: = Yeah) (= Yeah). So you could.	
776	Sue	So that's one (points to screen, suggesting that graph is one possibility for the solution).	

For the next 54 turns of speech the girls discussed at length the question as to whether either or both of the walker or cricketer (Tasks 4.1 and 4.2) should have turned around for their return journeys. Their graph (line 773 above) showed that the cricketer at the end of the second run was a long way from his starting point. Sue saw a conflict in this situation, "cause [in the original written problem] he goes back to the same place" (line 810, not cited) from where he began. The girls could not reconcile (a) the fact that the cricketer physically had to turn round in order to run forwards for the second run, with (b) the physics graph that required him to finish with zero displacement.

They practised moving the wheel backwards without turning it 180^0, and created a second graph (shown on line 834 below).

830	Cate	No we're not turning around.	
831	Sue	YEAH, but yeah.	
832	Cate	Just like (moves hand forward then backward with no turning around for the second run).	
833	Sue	OK.	
834	Cate	OK. (untangling the cord) . . Go yih, yih (motions with her hands). You've got to go up decelerate and return. . . Ready, go. (Both view the screen for three seconds) . . . Yeah! Because (touching the screen) he just keeps going. He doesn't have to decelerate (pointing to the start position) [i.e., on return run he does not slow down on returning to the start].	

When Cate examined the graph (line 834) she confirmed two details: that the graph now returned to zero displacement, and the cricketer did not "decelerate" for the return journey.

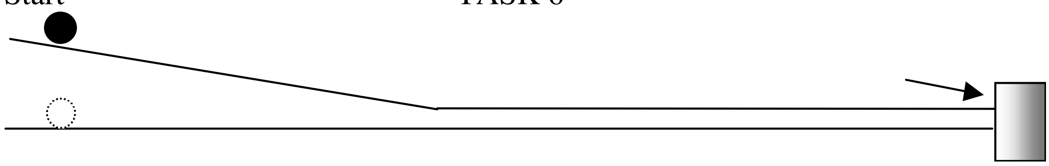
This extended exchange showed the girls considered two scenarios for moving the wheel, and produced a graph for each which they explained in detail. The girls came to realise that two tasks were the same problem in different guises. Cate and Sue sorted out their velocity/displacement graph confusion, and for the moment resolved the conflict between the actual behaviour of the cricketer (his turning around for the second run) and the physicist’s simulation (his not turning around in order to preserve the sign convention of positive direction).

The teacher discussed this issue with the girls later in the lesson (line 896 below). Cate’s reply (line 897) reflected another view held by physicists, that of treating bodies as point masses or “dots,” in which case turning around had no meaning (line 899).

896	Teacher	But in a PHYSICS viewpoint, (Cate: = Yeah) we might think of the cricketer running this way, stopping, and then running backwards, (Sue: = Yeah) to keep that plus and minus direction.
897	Cate	Yeah but the cricketer is just like a dot (pokes air). All you see is the dot nnnyyyt (finger forward) and it stops, and then it goes backwards.
898	Teacher	And then come back.
899	Cate	You don’t know if it’s turned around.

In the next vignette Mel and Hank began Task 6:

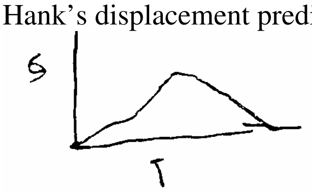
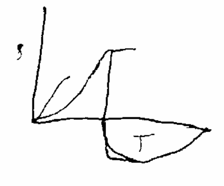
Start TASK 6



Finish Ball bounces back from a rubber block

Predict the displacement and velocity graphs, then imitate the motion using the wheel.

Their dialogue proceeded through the stages of interpreting the problem, predicting displacement and velocity graphs, setting up the experiment, and critically reviewing the outcome. In the process they made some common assumptions and common graph errors. Both boys made predictions quickly without discussion, Mel simulating the rolling ball with his finger on the bench as he wrote. Hank’s displacement graph (line 900, graph) was basically correct, but Mel’s graph confused velocity and displacement (line 901, graph).

900	Hank	(Hank reads the task and draws his displacement graph.) . . Displacement . . It'd come back to its starting position. . . Is that a displacement or (?)?	Hank's displacement prediction 
901	Mel	Yeah . . . (Mel traces the motion on the bench and continues to drawn his prediction) . . .	Mel's displacement prediction 

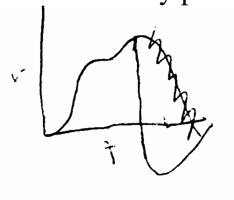
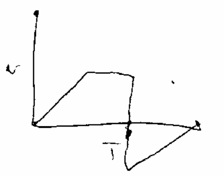
No students in the class remarked on the short period of acceleration as the ball rolled down the ramp, and all assumed that a ball rolling on a horizontal surface must slow down.

Hank (line 904 below) assumed when the ball reached the bottom of the incline it would slow down on the flat. Mel (line 907) considered the impracticality of turning the wheel 180^0 for the rebound. Hank agreed, making the more pertinent observation that the ball had to return to zero displacement (line 908).

904	Hank	(He picks up the wheel.) Umm . . down the slope . . It'd slow down to about there (touching the rubber block in the diagram for Task 6).	
905	Mel	You've got to think though because . .	
906	Hank	(He rolls the wheel.) Dit dit dit.	
907	Mel	You've got to think because we're not going to awkwardly turn it around and it goes like that (modelling with his hand on a pretend wheel) so . . it's going to be going backwards on . . (showing with the wheel on the bench).	
908	Hank	Yeah . . because it has to . . displacement has to cut . . it has to finish where it's started. So you've got to fall backwards (showing with the wheel on the bench).	

In line 909 (below) Mel observed that returning backwards involved a negative velocity. Hank agreed and refined his POE velocity graph by making changes (line 912, graph). They frequently used their hands and the wheel to help visualise the motion. Both velocity predictions showed an initial acceleration.

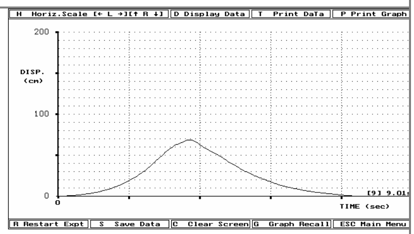
909	Mel	Yeah. . So the velocity graph is going to have negative velocity as well, won't it? . . . Because you go forward (Hank: = Yeah), and go back (moving his hand forward, then	

		back along the bench).	
910	Hank	Yeah, yeah . . .	
911	Mel	Looks like it's negative velocity (drawing a velocity graph).	
912	Hank	Yeah when it hits the wall it's going to plummet straight down (one hand touches the wall in the diagram, the other hand draws a vertical line downwards). [See the vertical drop in his velocity prediction on right.]	Hank's velocity prediction 
913	Mel	Yeah . . . umm . . OK Just about. (Mel sets up the screen.)	Mel's velocity prediction 

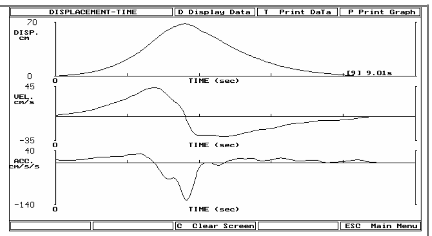
Hank claimed the velocity then slightly decreased (line 917 below) to the block, but his graph (line 912 above) was not consistent with this. Mel showed the velocity either constant or slowing to the block (line 913 above). Neither student drew graphs with precision. After the collision both graphs showed the ball accelerating to a stop.

Their next stage was to practise the wheel movement and record data. Mel and Hank found that carefully planned motion resulted in successful data collection the first time. Lines 917 to 929 recount a typical rehearsal, as they talked and motioned their way through the simulation.

917	Hank	Accelerate, then it would slow a tiny bit because it is on a flat, (moving the wheel as he speaks; Mel traces the path also), hit the wall, bounce back, then slow down.	
918	Mel	Well let's say (retracing the path by hand) . . . and then decelerating (on return).	
919	Hank	Yeah.	
920	Mel	OK (??).	
921	Hank	Comes along, fairly fast, (moving the wheel forward).	
922	Mel	Oh we've got to accelerate so we've got to go slow to start with, and he's just – if you release it.	
923	Hank	Yeah he has to accelerate.	
924	Mel	Yeah I know but you start off from a stop start (pointing to start on bench).	

925	Hank	Yeah – accelerate (moving the wheel), starts to slow down a bit, then he hits the wall, then he slows d-o-w-n (stopping the wheel) . . .	
926	Mel	Right . .	
927	Hank	Right?	
928	Mel	I guess that's kind of like um . . (taking the wheel and rolling it forwards to demonstrate).	
929	Hank	Accelerates down hill, slows, hits the wall, comes back, and slows down . . (finishing a practice run).	
930	Mel	And then to a stop. . . So 3 2 1 [counting down to start] (They collect their data). Lovely. . . (Hank puts the wheel down).	

His predicted displacement graph (line 901 above) contrasted with the simulation graph (line 930 above). Immediately Mel (line 934 below) chastised himself for his velocity-displacement confusion. He often spoke introspectively.

934	Mel	What was I thinking?! . . OK. (He displays the motion graphs. Both view the screen.) Our velocity thing was very good.	

The third example is based on a Type II task. Mel and Hank had created a random displacement graph that they copied into their POE notes and divided into sections for analysis. Other students used their screen displays for the same exercise. Mel described his graph section by section, as shown in Figure 5.6 below (the details of which need not be read).

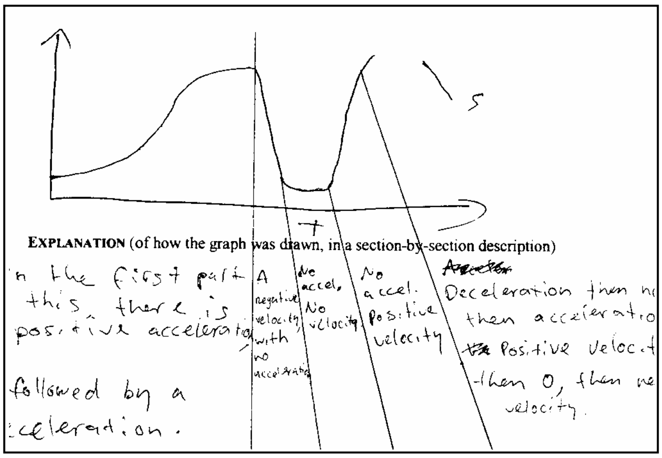
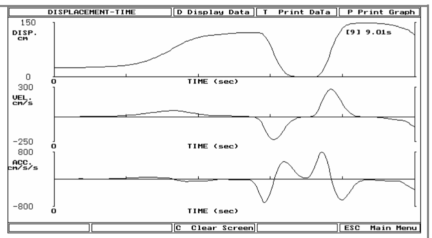


Figure 5.6. Mel divided his graph into sections for individual analyses.

To verify his predictions, Mel recalled to the screen the displacement-velocity-acceleration graphs for this experiment (line 290, graph).

290	Mel	Graph 8. It was this one. So we've got a . . . positive acceleration going into a negative acceleration just about . . . (touching the top displacement graph on the screen) so as soon as it discontinues climbing . . deacceleration [sic] . . finishes accelerating there . . a little bit of deacceleration . . . deacceleration . . .	

Both students continued for the next 30 lines of speech, gesturing between the screen and their POE notes, evaluating and making subtle adjustments to each other's predictions. They were able to compare the graphs vertically at the same points in time. Mel summarised the task by narrating a complete description of the random motion based on their displacement graph.

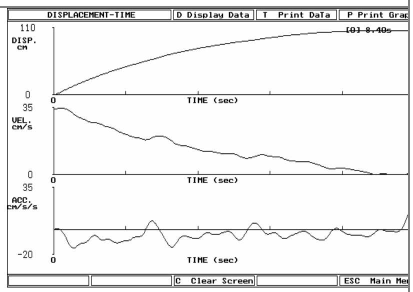
The following three examples illustrate inter-dyad visits. Barry's group called Mel "Einstein." On Day 4 Barry's group visited Mel and Hank to discuss Task 9.

> Tyson maintains that a body can have zero velocity, yet have an acceleration. Amber believes it is possible to have a velocity in one direction, and an acceleration in the opposite direction. Are either or both correct?

Barry believed Amber was correct (line 1269), but asked Mel his opinion, with which he obliged.

1269	Barry	We found that Tyson's wrong but Amber is right. But is it possible to have positive acceleration and negative velocity at the same time?
1270	Mel	I'll demonstrate (Mel picks up the wheel and re-sets the graph) . . . (To Hank) Could you get the keyboard for me? (Hank: = Sure) . . I'll say when. Go. . . . .

After two false starts Mel created a graph (line 1282 below, graph) and Barry's group was impressed.

1282	Barry	(= Oooh freaky!) (Ron: = Smooth)	
1283	Barry	Smoother than we can get it.	
1284	Gary	You've got a nice umm . .	
1285	Ron	Dead set.	
1286	Mel	(The acceleration graph appears.) Dead set. (Barry: Oooh) (Ron: Unreal) . . So what'd it say, umm (Mel reads his notes). . . (touching the screen on the velocity line [centre graph on right] showing the velocity is positive) velocity in one direction, and acceleration in the other direction. (Mel now touches the acceleration curve, which shows negative acceleration.)	

In line 1286 above Mel explained why Amber was correct. Hank joined in, and they illustrated the message of the graphs by pulling and pushing imaginary objects with their arms. Mel asked Barry (line 1293 below) if his explanation was of help.

1293	Mel	Right now? [i.e., Do you understand that now?]
1294	Barry	Kind of. It doesn't really seem that positive velocity and negative acceleration . . .

In the second example, Barry's group visited Mel and Hank, who assured Barry that an anomaly in one of their graphs was not significant: "As long as you've got the basic shape [touching the screen] you know it doesn't have to be exact" (line 772, not shown).

In the third case, when Dion and Alan from Group E entered their room looking for equipment, they overheard Mel and Hank talking through a problem. Dion offered a suggestion (lines 1213 and 1215 below).

1211	Hank	We need to do a graph where – the acceleration's in one direction and the velocity's in another?
1212	Mel	Do we?
1213	Dion	I know how to do it.
1214	Hank	Give some examples.
1215	Dion	(Dion picks up the wheel.) You get a ruler, . . and then you get a bit of tape at the bottom, and you put – you know those pendulum things we use? . . Yeah you put them on the bottom and then you tape it to there [i.e., tape the ruler to the wheel], and then you swing it, and the ruler will stay straight and go like that (Dion holds the wheel handle in one hand, and with the other demonstrates a pendulum motion by the rule).

Hank and Mel went on to adopt Dion's idea for creating oscillating graphs.

A reading of the student interviews and teacher journal helped create a description of the social interactions in the laboratory. The videotaped groups did not leave their rooms to visit other groups, though Dyad B sought out the teacher twice with questions about graph shapes. Groups from the main laboratory visited the videotaped dyads for three reasons: mostly to exchange ideas; sometimes out of curiosity about the video equipment; and late on the last day just to socialise. Groups in the main laboratory frequently compared graph results with their immediate neighbours. Chandra and Harry held lengthy and excited discussions which often attracted other groups to their bench.

Teacher: Did you find other groups came to you for ideas, or did you go to other groups very much?

Chandra: Yeah we did that constantly.

Harry: Other groups came to us also.

Chandra: They probably came to us more than we got back to them.

Teacher: What did they want to know?

Chandra: Our answers, what we got.

Harry: Just about the graphs and everything. How we compared to the others. If we got different answers then we had our argument and then we'd just decide on what was correct.

Chandra: Yeah. If we had an argument we'd go to another group to see what they got. (AS1030300)

As for the preferred size of groups, all of those interviewed agreed that two (or at the most three) students was ideal.

Jane: I'd say two (Tony: = Yeah). Three is a bit crowded, sort of can't share evenly (Tony: = Yeah). One (student) gets left out.

Teacher: And if you had four or five?

Tony: Some people don't want to do the work, they leave it to someone else . . . if it's two both share the work. (AS3020300)

Students spoke positively about the benefits of having to write POE explanations as the process forced them to think and keep on task. "I'd say it was beneficial because you actually have to think about what you're thinking" (Sue, AS2020300). Two groups wrote very little in their POE worksheets, and issues about their depth of involvement with the lessons will be taken up in section 5.4.5.

5.4.2.2 Discussion

The above analysis began with passages of dialogue in which students discussed problems and arrived at individual or consensual predictions. Secondly, it examined passages in which students conducted the experiment and displayed graphic data. At this stage students sometimes found the display confirmed their reasoning, which reinforced their scientifically based concepts. Otherwise, when confronted with contrary evidence, students reconstructed their explanations and in some cases repeated experiments to test their newfound explanations. The analysis concluded by inquiring into the optimal size of groups, and the reasons behind group interactions in the MBL.

> Assertion K5. Learning conditions in the MBL were conducive to fostering conceptual change.

The analysis examined instances supportive of this assertion, the conditions for change being: graphic evidence to engender dissatisfaction with prior conceptions; opportunities to construct new conceptions that can be seen to be intelligible, plausible and fruitful; and an atmosphere that is motivationally and socially conducive to constructing new understandings (Duit & Treagust, 1998). Evidence from POE worksheets, interviews and the teacher's journal showed that the majority of students took advantage of these conditions and showed some conceptual change.

> Assertion K6. Within and between groups, students engaged in a broad range of activities directed at creating and interpreting graphs.

This assertion may be appended with an extensive list of activities, which include:

- Converting a narrative description to simulated wheel motion. The process often involved negotiated discussion, marking tracks on the bench top, body and hand simulation movements, and practice trials.
- Evaluating the display to confirm or disconfirm predictions.
- Theorising, based on personal experience, knowledge of graph patterns, and comparisons with previous experiments.
- Expressing agreement, disagreement, and self-correction
- Interactively scaffolding understanding, correcting a partner, counterbalancing opinions, and resolving conflicts.
- Note-taking to maintain a record, and to crystallise thinking.
- Trialling ideas, predicting and proposing new experiments.
- Repeating experiments to confirm reconstruction of explanations.
- Crosschecking graphs and techniques with other groups.

Assertion K7. The display served as a shared resource for joint knowledge construction.

This assertion recognises the important role of the display in facilitating students' social construction of knowledge (see section 2.4.3).

Expanding on this assertion, students used steps and rules to:

- Verify existing beliefs;
- Analyse the graph, by dividing it into small sections for individual analysis;
- Identify and compare graph patterns with standard patterns representing constant velocity and constant acceleration; and
- Use the screen as a working diagram against which they held straight edges, measured and compared displacements and velocities, calculated gradients and areas under curves, and matched tabular data with graph features.

During some experiments students made assumptions that affected how they processed the tasks. Some students were unaware of this, and after having the assumption brought to their attention by their partner they repeated the task using an alternative assumption. Some common assumptions were:

- A body returning to its starting position automatically slows to a stop when it arrives. This includes balls rolling on a horizontal track or a cyclist cycling down a hill.

- For a body to return along a straight track it must rotate 180^0. This results in a distance-time graph instead of displacement-time graph.

The first assumption does not necessarily run counter to the physicist's view, provided the student states what was assumed in interpreting the problem. Students made the second assumption based on experiential grounds: a cyclist never cycles backwards, nor do cricketers run backwards. The convention of assigning and adhering to a positive direction for displacement was a new concept for novice kinematics students.

Some common errors and misconceptions made by students were:

- To draw a velocity-time graph in place of a displacement-time graph. Some students self-corrected this error in one experiment, only to repeat the same error in a later experiment.
- That deceleration meant returning to the origin and slowing down. This is in fact acceleration.
- At the moment of rebound an object has zero acceleration, since it is stationary. In fact it has a large negative acceleration.
- A displacement-time graph is a "picture." A child sliding down a slippery-slide is described by a descending displacement-time graph concave upwards. It is actually convex upwards.
- The point of maximum displacement on a velocity-time graph is at the point when velocity is a maximum. It is actually the point where the velocity curve meets the time axis.

Students believed that group sizes of two or at the most three were ideal for the MBL. This contrasted with the finding of Alexopoulou and Driver (1996) that students in groups of four were less constrained than groups of two when reasoning on written physics problems. However, students in the present study were more accustomed to group work than those studied by Alexopoulou and Driver, and the purpose of the activities was different. Furthermore, the pairs of students in the MBL were complemented by a third actor, the display, that presented definitive data which guided the students in their deliberations. Further, the physical layout of the MBL and sharing the keyboard and wheel sensor was suited to two or, at most, three students. Four students would have overly crowded the available space.

5.4.3 The display and working memory

Assertion K8: The kinematics graphic display supported students' working memory.

This aspect of the analysis examined the extent to which the display acted as an aid to working memory (Pennington et al., 1996) (see section 2.4.2.2). Mindful of many claims that MBL methods and graph displays support students' working memories (for example, Linn et al., 1987; Linn & Songer, 1991b), the transcripts were read for evidence of this. Questions were asked of the data about the three components of working memory. Did the display support students' (a) concurrent storage and processing of information, (b) maintenance of information over time, and (c) level of alertness? Working memory refers to the ability to apply these components in combination or until some action can be initiated (Pennington et al., 1996).

Concerning the first component, (a) concurrent storage and processing of information, the evidence suggests that students' memories were freed from other concurrent demands, such as drawing pencil-on-paper graphs, or manipulating equipment and measuring instruments. The analysis found no evidence in this MBL that students "spent more cognitive energy on performing the experiment than on learning the physics," as was reported in another MBL (Clark & Jackson, 1998, p. 1). When creating a graph, students began with a visual image of their expectation (that is, their prediction graph), were confronted with a real-time data display, then compared the two through such activities as critically analysing, comparing, accepting, rejecting, interpreting, explaining, concluding, measuring, and calculating.

The second component required that students (b) maintain information over time. As often as students referred to the screen image they refreshed their information. The examples previously analysed showed they did this continually by silent viewing, touching, measuring, discussing, comparing and copying. The display image itself "maintained information over time," in parallel with the students' mental processing of the information. In computer parlance, the display acted as a "backup" of their memory banks.

The third component was the students' (c) level of vigilance, maintained over the duration of the task. Dialogue previously analysed showed that students characteristically focused on the display until they completed the task at hand (for example, section 5.4.2). The display kept students alert to multiple aspects of the data and their interpretation. Of the videotaped students, the only exception to students maintaining alertness was one occasion (section 5.3.1.1, their lines of speech 1142 to 1149) in which Sue and Cate grew frustrated and bypassed a task.

Furthermore, the visual display imprinted mental images which students recalled at appropriate times. Jane knew what the velocity graph for a falling object should have looked like, having seen one previously. When presented with a new graph purporting to represent a falling object, she rejected it as wrong. Mel recalled that the displacement graph for acceleration was concave upwards, which helped him avoid confusing acceleration and deceleration on a number of occasions. From transcripts of interviews some students said they were able to recall mental images of specific graphs for some days after the experiment. "Oh it just comes to me . . I don't know . . easy" (AS2020300). When students viewed the triple graph display (displacement, velocity and acceleration graphs) they interlinked features on the screen, and beyond the screen to the experiment and task narrative.

5.4.4 Teacher interactions with dyads

During the laboratory activities the teacher acted in three roles: manager, teacher, and researcher. As a manager he maintained the hardware and trained students in the correct use of the software and sensors. As a teacher he facilitated learning by moving from dyad to dyad, observing and asking questions, encouraging and motivating students. This section examines the role of teacher as facilitator, using the annotated transcripts of audiotapes, student interviews and teacher journal.

5.4.4.1 Analysis

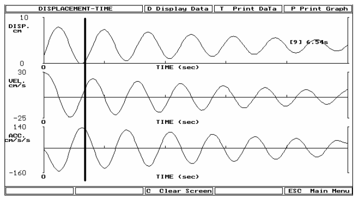
The following lengthy exchange on Day 4 illustrated how the teacher made effective use of probing questions. Mel and Hank were searching for evidence in graphs that a body could have zero velocity with non-zero acceleration. They became so interested in creating graphs that they forgot their original purpose of analysing them (line 1376 below) and concluded their discussion.

1376	Mel	Yeah . . Right, well. (He returns to the Main Menu.) That's about as much as we can do . . . (Mel fiddles with the Main Menu, until the teacher enters.)	

At this point the teacher entered and asked a simple question to draw them out.

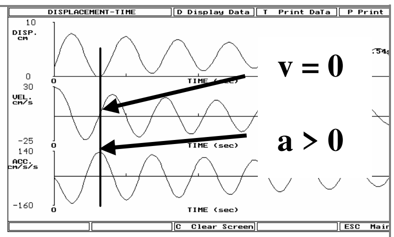
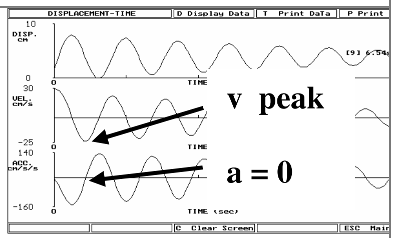
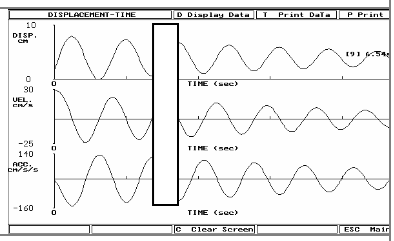
1377	Teacher	So what did you find about the possibility of having zero velocity yet have an acceleration?	
1378	Mel	I don't think it's possible.	
1379	Teacher	You don't think it's possible?	
1380	Mel	[To Hank] What do you think Hank?	
1381	Hank	No cause, you don't know what velocity – well when you accelerate you're going to get velocity, aren't you? [i.e., both velocity and acceleration are needed together.] . .	

Neither boy believed such a motion was possible (lines 1378 and 1381 above). The teacher then prompted the students to display a pendulum graph he saw them create earlier, and asked a leading question (line 1382 below).

1382	Teacher	Well you've examined a few different types of motion. Take the pendulum motion. (Mel: = Well,) Just go back to the acceleration curve for that (Mel displays this) . . . Alright. . . . Now we ask the question again: Can a body have zero velocity yet have an acceleration? (Mel and Hank view the screen for 2 seconds.)	
1383	Mel	Ah. It can (smiles).	
1384	Hank	(one second later) Ooohhh! [He understands]	
1385	Mel	OK.	
1386	Teacher	It can?	
1387	Mel	I suppose like . . as soon as it passes through (picking up a rule to act as a pendulum) the centre it's got acceleration moving that way (Mel's thumb points backwards), and then it stops (at the extreme amplitude) so it's still got a . . right yeah (Mel smiles as though embarrassed about his failure to see the point earlier.	

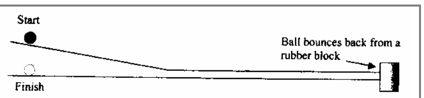
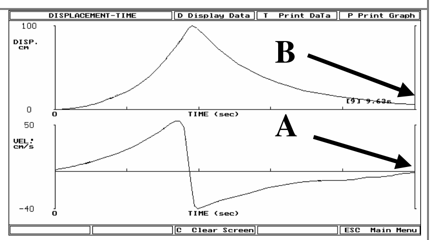
Immediately the boys saw the velocity and acceleration graphs they grasped the answer, and Mel translated the display to a simulated motion of a pendulum (line 1387). The teacher continued to draw out the students. Though Mel carried most of the conversation in the following dialogue (lines 1388 to 1397), Hank signified periodically that he was following.

1388	Teacher	Now where on the graph did you get that?	

1389	Mel	Ahh – just at the peak here [i.e., of the acceleration graph, shown on the right where a > 0], where you've got zero (Teacher: Zero velocity) you've got zero velocity there [on the right where v = 0].	
1390	Teacher	So peak acceleration zero velocity (The teacher reads from Hank's notes). . .	
. . . .			
1392	Teacher	Can you find a case of having no acceleration, and yet peak velocity?	
1393	Mel	Oh right. Umm . . Yeah, that is the case all the time . . Like (touching the screen) no acceleration you've got a peak there (pointing to its peak velocity immediately above a zero acceleration, as shown on the right), no acceleration you've got peak there, so	
1394	Teacher	(The teacher picks up a rule from the bench.) Some students find it helpful to line the graphs up vertically (giving the rule to Mel).	
1395	Mel	(Mel holds the rule against the screen vertically.) So you've got peak acceleration there, and that's zero [velocity] there, peak acceleration there, and zero [acceleration] there.	
1396	Teacher	Yes.	
1397	Mel	I suppose that's true because (Mel holds up the rule as a pendulum) its greatest velocity would be just here (pendulum vertical), because you've still got your acceleration acting on it here (just before the vertical) and you've got deceleration acting on it there (just after it passes the vertical). (Hank: = Yeah), so its peak velocity is here (vertical), that's zero acceleration acting on it.	

Mel (line 1397) spoke introspectively ("I suppose that's true . . ."), describing the link between the graphs and his pendulum to give an accurate and detailed explanation. The entire interchange lasted 11 minutes, the teacher posing both simple and probing questions, giving technical help such as suggesting the use of a rule (line 1394 above), and making an occasional suggestion. Mel, with the periodic supportive comment from Hank, expressed himself at a level well in advance of the coursework.

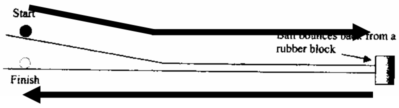
Twenty minutes earlier the teacher had joined Dyad B, who were comparing the graphic results of a rolling ball experiment with their POE predictions. The dialogue illustrates how the teacher's questions about the display gave the students opportunities to express themselves at a greater depth than they might ordinarily have done so. In line 1406 below the teacher (referring to the velocity graph, the lower of the two graphs on line 1410) asked if the ball rolled back to the start. Tony's reply was in error. He pointed to the velocity graph returning to zero velocity (line 1410, graph at A), instead of the displacement graph which did not quite return to a zero displacement (at B).

1406	Teacher	So the velocity becomes negative (Jane: = Yes) because it's going backwards. Yes. . . . Did it get back exactly to the start? In your model? (All peer at the screen.)	 Ball rolls right, rebounds to the left
1407	Jane	Ahhh. No. . .	
1408	Tony	Which one? . . Our prediction?	
1409	Teacher	Well – on the screen . .	
1410	Tony	Yeah . . It looks like it did there (touching the screen velocity graph at A).	
1411	Teacher	That's the velocity one.	
1412	Jane	No on the other one it didn't quite (touching displacement graph at B).	

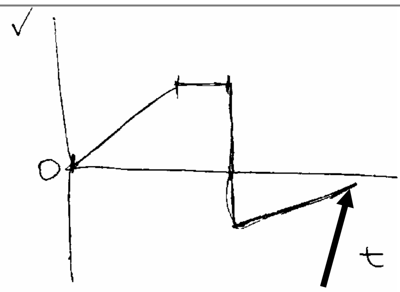
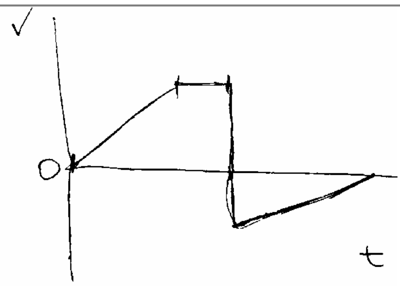
Jane corrected her partner (line 1412 above) and showed on the displacement graph that the ball did not quite return to the start.

The teacher agreed with Jane, but said the small difference was not significant (line 1413 below). Jane was quick to point out (line 1414) that they had in fact created the graph that way intentionally, for she reasoned the return path of the ball was slightly shorter than the outgoing path.

1413	Teacher	On the other one it didn't quite . . But that's no big difference, is it.	

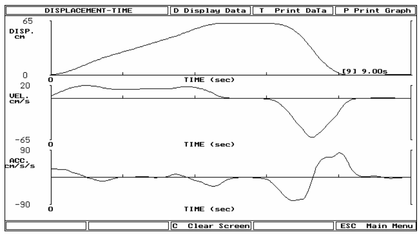
1414	Jane	(Touching the diagram to explain.) Well we figured that that would be probably a longer distance to travel than that one there.	Path to the right is longer than the  return path to the left.
1415	Teacher	The top travel would be a longer distance.	

Tony then tried to relate the shorter return journey to his rather inaccurate copy of the screen velocity graph (line 1418 below). He thought that if the ball did not return to the origin the velocity curve would not return to zero. Again he confused velocity with displacement curves. Jane corrected Tony (line 1420 below) by explaining the graph in terms of the actual movement of the wheel.

1418	Tony	Yep . . . So would that actually reach to about there? (He points to part of the velocity graph he copied roughly from the screen. The velocity line did not reach the time axis	
1419	Teacher	Well you are pointing to the velocity curve, and showing the velocity curve did not quite come back to zero velocity.	
1420	Jane	But it would have because it did come back to – not travel – yeah . . zero velocity. [Jane says this to Tony, helping to correct his understanding.]	
1421	Teacher	So Jane you are saying it would have, because it came back to being stationary (Jane nods), with no velocity, Tony you were thinking of that (touching the velocity graph shown on line 1418) as being a slight displacement difference.	
1422	Tony	Yeah. (Tony slightly extends the graph line so that it touches the time axis. He later makes a better copy of the screen graph.)	

As exemplified by Jane, students often spoke confidently about their graphs and interpretations. They surprised the teacher with their propensity to extract from the tasks more aspects for consideration than were originally intended.

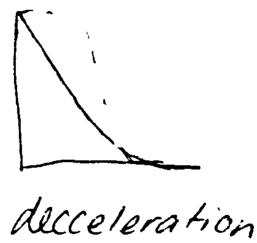
Sometimes the teacher sensitised students to interesting features of their graphs, to which they paid attention after he left. Mel and Hank had created a graph of a cyclist riding up a hill and then coasting back to the start. The teacher noticed with this task that virtually all students assumed the cyclist would brake to a stop at the bottom of the hill. For example, Mel's graph (line 479 below) showed the cyclist coming to a stop at the end of the graph. In line 486 the teacher pointed to this feature and suggested the boys comment on it.

479	Mel	Yeah OK . . 3 2 1 [counting down to start]. (He starts the graph. Hank rolls the wheel, stopping at the end) 1 2 3 4 1 2 1 2 [seconds]. (Both view the screen.) Excellent. (Both sit to copy the graph, and write explanations.)	
480	Teacher	Are you happy with your graph?	
481	Mel	Umm – yep!	
482	Teacher	Alright.	
483	Hank	I think so.	
484	Teacher	I just notice how you drew the wheel back, as she coasted down the hill.	
485	Mel	Hmm hmm,	
486	Teacher	How did you move the wheel? . . Don't remake the graph, but just be critical of how you coasted back down the hill and tell me what you did later. (Mel displays acceleration curves of the last graph.)	

After the teacher left, Mel and Hank discussed the last section of the graph, whereupon they added to their POE explanation: "Assuming she braked at the bottom of the hill."

The transcripts showed no occasions during the four lessons when the teacher encouraged inter-group liaisons, and the reasons for this can only be conjectured. With thermal physics graphs took minutes to develop, and sometimes turned out poorly due to experimental shortcomings. In such cases the teacher encouraged students to look at the results obtained by other groups. However, kinematics graphs were directly controlled by hand-movements of the wheel, and were reproducible in seconds. Students repeated data collection until the graph met with satisfaction. The teacher therefore had less reason to suggest they compare graphs across groups, unlike the situation (discussed in section 4.4.3.1, line of speech 656) in which he encouraged Mike and Ivan to compare their inaccurate temperature graph with that of another group

In reading and re-reading the transcripts it became apparent at times that the outcomes of teacher-student dialogue were sometimes problematic. On three occasions when Sarah asked for assistance, the teacher's answers missed the point of her query and devolved into global explanations. For example, Sarah and Cate spent considerable time discussing whether deceleration (line 348) was the same as negative acceleration (line346).

344	Cate	We're all confused (both smiling)	
345	Teacher	Yes I can see that	
346	Sarah	We thought negative when we started slow and then went faster (backwards, indicating with her hand) [Her POE sketch shown on the right is correctly labeled 'negative acceleration']	
347	Cate	Yeah	
348	Sarah	And then we did fast (backwards) and went slower. Negative. And they're different (moves hand in arc concave down, then in arc concave up) [Her POE sketch shown on the right is incorrectly labeled 'deceleration']	

The teacher missed the nuances of their confusion, because he failed to ask questions about their present understanding. Instead, he took control of the wheel and began a series of demonstrations of deceleration. Eventually he summarised his explanations (line 396).

396	Teacher	So even though I'm coming backwards (shows with wheel), I'm still decelerating . . . (both girls appear not to keep up with the teacher's explanation, they show no response to this last statement) and if I'm still decelerating, see that the curve (now holding his hand next to the screen) is still coming over (Cate nods approval), all the way decelerating (Sarah nods approval) [NOTE: A nod doesn't necessarily indicate understanding or approval of course] . . . (Walks to other side of the screen) So the deceleration is not only here (first half rise of screen graph) but is that decelerating (second half fall of graph) (Sarah nods approval, Cate is motionless)? . . . Well you just select what graphs you want to save, if any. . .

A careful reading of the transcription showed that the students had gained little from the teacher's intervention. Finally, Sarah summarised her explanations.

430	Sarah	(Sarah draws from memory, the screen is blank.) There were the two types of negative acceleration (hand curves up) . . which is that curve, . . . there was DEceleration (she draws concave down; then practices with her left hand to model up and down curves) . . . like fast slopes, that went (cups hand down)

Sarah's conclusions were unchanged from those of her sketches in lines 346 and 348 above. The latter graph and explanation of deceleration still showed an incorrect understanding. Notwithstanding the time he spent with Sarah and Cate, the teacher failed to recognise an enduring problem they had with understanding some basic graph patterns. This was exacerbated by their misnaming data files, and hence being unable to recall graphs for later analysis.

Twice, possibly three times, the teacher led conversations beyond the students' depth of understanding, which was an ineffectual use of everyone's time. For example, the teacher side-tracked Mike and Hank's analysis of the acceleration of a falling mass, with a discussion of what happened when the falling mass hit the floor. For 23 turns of speech he spoke about electrostatic repulsion of electrons by electrons, and compared electrical and gravitational forces.

The transcript of the teacher's audiotapes during the four lessons showed that he spent as many minutes speaking with the two videotaped dyads, as he did speaking with the ten groups in the main laboratory. This imbalance was a consequence of the research, and the effect on the class will be addressed in the following section.

Each day in the main laboratory his dialogue took on a different emphasis. On Day 1 the teacher visited many groups briefly, giving technical advice, reminding students to make predictions, and answering questions of a general nature. On Days 2 and 3 the principal focus changed to asking and answering questions about what students were doing and learning. Day 4 was unusual in that the teacher spent twice as much time with the videotaped dyads as he did with groups in the main laboratory. By the latter half of Day 4 two groups and three or four other individuals in the main laboratory recorded their POE notes sparingly, and tended to drift off task. Gary and Nathan were asked about this the following week (AS1140300).

Teacher: Now I notice as time went by you tended to write fewer explanations. Why would that be?

Gary:	I think it was because it started to get repetitive, like (Nathan: = Yeah) the same things, we weren't looking into the questions as much, but . .
Nathan:	Just kind of trying to get them [the tasks] done, before the lesson ends. Just you know, probably rushing it too much.
Teacher:	Now when you say trying to rush looking into it . . .
Gary:	Yeah like you know how you said to the class there was more to it than we first thought (Teacher: = Yes), we weren't looking at stuff in depth, like seeing that it was the same type of graph type thing.
Nathan:	Maybe if we were told what to look for before we started the experiment, we could have looked more into it.
Teacher:	Would it have been better if I had more time to just talk to each group?
Nathan:	Yeah.
Gary:	Yeah there's a lot more to it than what we thought.

As shown in the above exchange, Gary and Nathan felt that many graphs seemed repetitive, although they did acknowledge, "there's a lot more to it than what we thought." The teacher's question about his not spending sufficient time with each group reflected a journal notation he wrote after Day 4. Other interviewees made similar comments to Gary and Nathan. Some students who wrote sparse POE notes said they were unsure of what to write, or what was expected, and they would have benefited from more personal guidance. The same students said nevertheless that the worksheets forced them to think about what they were doing.

After Day 4 in the laboratory the teacher conducted two follow-up whole class lessons based on selected extracts from the students' worksheets. These lessons helped students to clarify their understanding of tasks undertaken during the four MBL lessons.

5.4.4.2 Discussion

> Assertion K9. When the teacher asked probing questions, they often stimulated deeply processed responses linked to graph features and the experimental phenomena.

Table 4.1 in section 4.3 listed a number of characteristics of students processing ideas at a deep level, many of which were identified in the teacher-student dialogue above. Students expressed themselves at a deep level apart from the teacher's presence. However, when the teacher joined in the dialogue he prompted them to extract meaning from the display that might otherwise have remained hidden to them. When the teacher became part of the constructive process students were stimulated to reflect more critically and integrate ideas about graph features. The two vignettes at the start of the analysis were extracts selected from a total of twelve extended exchanges between the teacher and the videotaped students. These dialogues support Assertion K9.

The assertion also implies that the display contained within itself a rich potential for deep analysis. The corollary of this assertion would infer that students having fewer interactions with their teacher are more limited in their opportunities to function at a deep level. The following section will return to this matter.

An important aspect of the teacher's activities was to maintain functioning hardware and to give instruction as needed in software usage. Students had few difficulties using the equipment. From a technical aspect, problems arose when students either forgot to save graph data, or did not save data using systematic file names (as had been requested). This is a matter of refining software to minimise students' self-inflicted errors. Since the teacher is the author of the software used in the research, changes for improvement can be made.

By way of caution to the teacher, the analysis showed that when approaching groups he needed to listen carefully to students so as to understand clearly what stage they had reached, and to operate at and not beyond their knowledge level.

5.4.5 Student limitations and delimitations in the kinematics MBL

The analysis thus far has identified a number of constraints to learning in the MBL. Some of these are attributable to personal limitations of students. Within six months of the kinematics research, 7 of the 29 students left the physics course due to not coping with the academic demands of the subject. The academic ranks of these students were 19, 20, 24, 25, 27, 28 and 29.

This section is concerned with identifying constraints external to the students that delimited their learning. The data sources used were the student POE worksheets, transcripts of dialogue, teacher journal and student interviews. The discussion that follows seeks to interpret the data in terms of how the structural framework of the MBL and the teacher's role delimited student learning.

5.4.5.1 Analysis

The teacher and students at times had different perceptions of what was expected with the tasks. The teacher assumed students would use the equipment, approach tasks and draw conclusions perhaps as he might have himself, whereas students often completed the tasks and handled equipment differently.

As a first example, the teacher anticipated students would explain the gradient of a downwards-sloping displacement curve in terms of a negative velocity. Eighteen of the 29 students failed to do so. Though they may have had a tacit understanding of the directional concept of velocity vectors, they did not make this explicit.

Secondly, Task 2 required that students compare acceleration and deceleration graphs. The teacher noticed that students manoeuvred the wheel in such a way as to confuse the relationship between direction of travel and graph shape. Only eighteen students produced and described correctly the displacement graph for deceleration. Consequently a large minority of the class failed to establish a clear understanding of displacement graph patterns.

Thirdly, Task 3 required that students create a displacement graph of random motion, then "break the graph into small sections, and compare the sections with the sample graphs from the previous tasks." The teacher assumed the students would divide their graphs into elemental sections, each representing one of the seven patterns developed in Tasks 1 and 2, and thence describe each section. Carl was one of only seven students who divided and described the sections as anticipated, as shown in Figure 5.7.

However, twelve students divided their graphs into large sections, each consisting of multiple motion patterns, as seen in Garth's diagrams in Figure 5.8. His POE notes show a mismatch between the teacher's expectations and his attempt. These students omitted many details in their interpretations of the random graph.

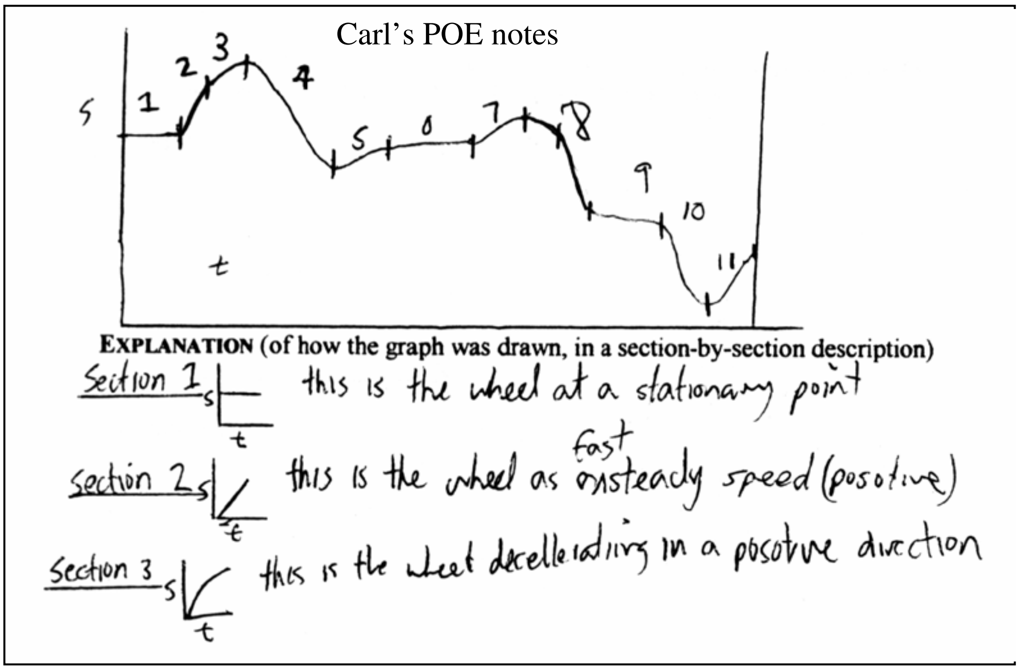


Figure 5.7. Carl's POE notes show how he divided this graph into small sections for analysis.

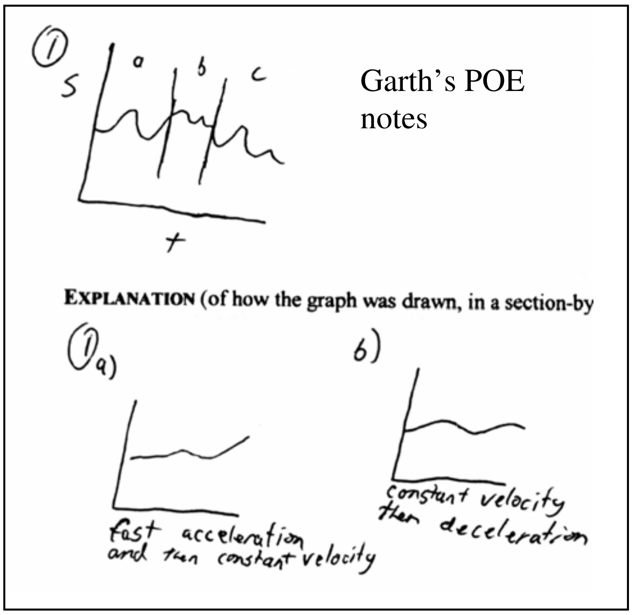


Figure 5.8. Garth's POE notes show how he divided his graph into large sections, contrary to the teacher's expectations.

A fourth example of students not acting as the teacher expected, was in their handling tasks where the moving object returned to the origin. Many turned the wheel around 180^0 for the return journey, which introduced a direction confusion. The teacher was aware that his perceptions of the tasks and those of his students differed. He wrote in his journal after Day 4: "It seemed to me important for students and teacher to understand each other and work together closely." (AJ100300)

The size of the class was a factor that affected the quality and quantity of the teacher's interaction with students. During the four laboratory sessions he spent 107 minutes speaking with the four videotaped students, and about the same time with the other 25 students. Two-thirds of his sequences of talk with students in the main laboratory were of a supervisory nature, and only one-third were responding to or asking questions about the experiments and display. Few teacher-student interactions reached a deep level because conversations were short, as compared to long conversations with the videotaped dyads. On Days 3 and 4 two dyads and two or three other individuals wrote minimal POE notes in contrast to their first two days' notes. The teacher wrote in his journal for Day 4: "The room seemed very crowded with 29 [students], an impossible number." (AJ030300)

Time constraints, the students were told, were not important. They were reassured that tasks could extend through the following lesson. By the end of Day 4 one half of the groups had not commenced the final task. Nevertheless some students when interviewed said they felt obliged to rush their experiments, and this affected the quality of their explanations. Nathan raised this in an interview (AS1140300):

Teacher: I notice as time went by you tended to write fewer explanations. Why would that be?

Nathan: Just kind of trying to get them done, before the lesson ends. Just you know, probably rushing it too much.

Chandra and Harry were meticulous with some of their early tasks, and this interview excerpt tells how it affected them (AS1030300):

Teacher: To what extent was time a limiting factor in everything you did? Would you have preferred more time?

Chandra: Probably one more lesson I suppose because we couldn't really get to the end.

Harry:	We're pretty sure that we were going a bit slow because everyone else had finished by then.	
Chandra:	Yes, so we started rushing things, and I don't think we were taking into account everything that needed to be observed, so we overlooked a few things.	

While the students generally handled the MBL software adeptly, Dyads B and C had difficulties using certain features. Cate and Sue, as noted in section 5.3.1.1, failed to master software procedures for naming files and recalling graphs. This affected their success with tasks on Day 3, and subsequently their satisfaction and motivation. Compounding this, both girls appeared unusually tired throughout the third day. Dyad C tried to use the display of tabular motion data but failed to read the table headings carefully, which meant the data conveyed little meaning.

A small number of students were constrained by their personal work ethic and the limited learning skills they brought to the lessons. The teacher said about some students on Day 1: "they were just sitting there letting someone else do all the work" (AT290200). Rick made very few POE notes "because he didn't think they would be collected" (AS2140300). In the last half of Day 4 Alan and Dion paid a social visit to Dyad A that irritated Mel:

1226	Mel	(Mel makes a verbal and visual remark to Dion and Alan who are out of camera vision, making shadow puppet hand signs in front of the camera)

Chandra spoke in an interview about the "jump from Year 10 to 11" and how, six weeks into the physics course, the level of expectations was higher than that to which they had been accustomed.

The teacher's summation of many of the students was: (a) They respond positively when given frequent guidance, (b) they have few skills of the autonomous learner, and (c) "they do the best they know how" (an expression he used frequently). When Garth was asked why he wrote so few observations and explanations, he responded: "Cause we didn't get much of the detail when we actually did it, because I don't think we were looking for that as much" (AS1140300). It was only during the post-MBL class discussion that they consolidated many of the concepts of the MBL lessons. Two lessons after Day 4 in the MBL the teacher asked students why they had made little written comment in the "explanation" section of their POE worksheets. His journal read: "One boy said they didn't know what/how to write or expand but they understood the ideas." (AJ100300)

5.4.5.2 Discussion

> Assertion K10. Student learning is delimited in part by the teacher's preparation for and structuring of the MBL lessons.

The other constraints identified in the analysis were: different expectations held by teacher and students about how to manipulate equipment, process tasks and write POE explanations; students' lack of facility with some software features; students' perception that they were expected to complete all tasks within four lessons; and students' limited academic experience at this level. All of these can be construed as delimitations, some of which lie within the control of the teacher and lead to Assertion K10. To improve learning in this MBL, (a) the lesson structure should alternate short periods in the MBL with whole-class discussions, and (b) experiment preparation should include continuous refinements of the MBL software, and extended prior practice with the MBL materials.

The first recommendation conjectures that interspersing whole-class discussions at shorter intervals would assist the teacher to gain an earlier awareness of what students were thinking and doing. Driver et al. (1994) state clearly that "if teaching is to lead students toward conventional science ideas, then the teacher's intervention is essential" (p. 7). Otherwise the student is left to discovery learning, which is ineffective or even detrimental for lower ability learners (Snow & Yalow, 1982). The teacher estimated about seven of the students would fall into this category, given the demands of the physics course. The teacher's intervention includes leading class discussions as well as circulating amongst students in the MBL. During the research period the teacher interacted with dyads individually. Whole class discussion led by the teacher may identify and define common student problems. Further, students would be able to share their results and consequently scaffold their learning more effectively. More frequent whole-class discussions may benefit less academic and less motivated students, by lessening frustration due to lack of success, and lack of concentration due to fatigue.

The second recommendation recognises that, despite the students practising with the MBL materials prior to Day 1, the time allowed was insufficient. Further, refinement of the software can minimise the occasional problem of students forgetting to save data, though with kinematics experiments new data can be regenerated quickly. Simple steps such as marking the top side of the wheel sensor and marking a positive direction arrow to the bench top may alleviate some of the direction confusion that crept into the graphs. MBL software and hardware are never foolproof, and their development and maintenance should be a continuing process.

The large class of 29 students as a factor delimiting the number and quality of teacher-student interactions was beyond the control of the teacher. The teacher himself felt that the quality and frequency of teacher-student interactions was seriously impaired with the large class size.

5.5 A SUMMARY OF THE KINEMATICS MBL

This chapter examined in detail how a class of 29 students studied kinematics during four laboratory sessions. The chapter began by describing the actors and networks of interactions in the kinematics MBL, and five stages through which students progressed in handling tasks: (a) understanding the problem and predicting, (b) setting up and commencing the experiment, (c) collecting data and observing, (d) analysing, and (e) explaining the results. Attention was drawn to some differences between kinematics and thermal physics in the network relationships, also to some tasks peculiar to kinematics (Type II tasks) that began with an analysis of previous data rather than an experiment. The chapter analysed many aspects of the role of the display, and teacher-student interactions, a summary of which is presented as 10 assertions in Table 5.2. The chapter concluded with a brief discussion of ways in which student learning was delimited by conditions in the MBL.

Table 5.2

Assertions From the Analysis of the Kinematics MBL

The role of the display in students' dialogue
Assertion K1 Students viewed the display, almost exclusively, as representing the experimental phenomena or task problem.
The level of student-display interactions
Assertion K2 During student-display interactions, while students' activities ranged from fulfilling basic requirements to deep level cognitive processing, the dyads completed the majority of tasks at a deep level of mental engagement.
Assertion K3 Students' deep approach to learning was supported by the enduring nature of the display.
Students' assessment of graphic data
Assertion K4 Students critically evaluated the appearance of the graphic display.
Dyadic discourse and graph interpretation
Assertion K5 Learning conditions in the MBL were conducive to fostering conceptual change
Assertion K6. Within and between groups, students engaged in a broad range of activities to create and interpret graphs.
Assertion K7. The display served as a shared resource for joint knowledge construction.
The display and working memory
Assertion K8. The kinematics graphics display supported students' working memory.
Teacher interactions with dyads
Assertion K9. When the teacher asked probing questions, they often stimulated deeply processed responses linked to graph features and the experimental phenomena.
Student limitations and delimitations in the thermal physics MBL
Assertion K10. Student learning is delimited in part by the teacher's preparation for and structuring of the MBL lessons.

CHAPTER 6: DISCUSSION OF LEARNING IN MBLs

Drawing on the analyses of chapters 4 and 5, this chapter discusses the commonalities and different features of MBL thermal physics and kinematics. Woven throughout this chapter are responses to the objectives and research outcomes raised in section 1.2: The objectives of the research program.

The interpretation of the first question (section 1.2), how do Year 11 students learn physics within the context of a constructivist MBL, is presented in the narrative summary of the next two sections, which describe student learning common to two disparate branches of physics. More specifically, section 6.1 responds to the question (section 1.2, question 3), what are the patterns of interaction between experimental phenomena, computer display, individual students, collaborative groups, and the teacher? Then section 6.2 presents eight assertions in response to the question (section 1.2, question 4), how are students' negotiations of new understandings mediated by the computer display, and to the third outcome (section 1.2), about how the teacher facilitates learning.

6.1 ACTORS AND NETWORK RELATIONSHIPS IN THE MBL

In previous studies of school laboratories equipped with computers, researchers have described classroom relationships in either of two ways. Firstly, when their focus in on social interactions, the students are of prime importance to the network of relationships, and the computer display and other inanimate artefacts are treated as context. Subsequently, to enhance student interactions and learning, the solution is seen to lie in adjusting the context, for example, by attaching a second keyboard (Light, Foot, Colbourn, & McClelland, 1987) or improving the software (Hutchings, Hall, & Colbourn, 1993). Secondly, when their focus is on the technology, the social entities become the context. Full advantage of the technology may then require adjusting how students use the computer, such as by re-writing their worksheet tasks (McLellan, 1994). In either case, as Bigum (1998a) points out, a change in one component results in a readjustment of all the other elements and their relationships. Hence he argues against treating any of the components of the classroom as context, simply to be described, and favours using an actor-network theory (ANT) (Bigum, 1998b; Lee & Brown, 1994). With ANT, there are no distinctions between the social (teacher and students) and non-social elements (such as the display, worksheets and apparatus). All are treated as actors (active participants) shaping their involvement with each other in a network. The actors in this study were identified as individual students, dyads, POE worksheets, sensors, apparatus, display, students' prior concepts, history of recent experiments, and the teacher (Figures 4.1, 4.2 and 5.2) (cf. Roth's (1996) description of actors in the network leading to the successful publication of a scientific report).

While aspects of ANT have been applied to classroom interactions previously (for example, Roth, 1996), this is the first study known in which it has been used for an MBL. Raising the status of inanimate objects enables the researcher to describe better the reciprocal nature of the interactions between animate and inanimate objects. In the case of McLellan's study (1994), only the students and teacher displayed two-way interactions, and inanimate objects such as the display were only acted upon. The present study identified reciprocal relationships between inanimate objects and people in the MBL (sections 4.1.1 and 5.1.1). These are shown as bi-directional arrows in Figure 4.1, 4.2 and 5.2, and support the earlier work by Kelly and Crawford (1996), who illustrated in a similar form the interactions between student/s and display: "Thus, for each way the computer acts as a member, there correspond instances of students employing the computer representation. The computer must be recognised to participate" (p. 701). Their study is extended here to incorporate other actors, these being the sensors, experimental apparatus and the POE worksheets in the simplified diagrams of Figures 4.1 and 5.2, and additionally the students' prior knowledge, other dyads and the teacher in Figure 4.2. Relationships between the actors in the MBL were identified by viewing the videotapes. The student dyad was central to all interactions in the laboratory.

In both thermal physics and kinematics laboratory classes, the students' activities were characterised by five stages: (a) understanding the problem and predicting, (b) setting up and commencing the experiment, (c) collecting data and observing, (d) analysing, and (e) explaining the results. In the few research reports of MBLs incorporating a POE format (Friedler et al., 1990; Linn & Songer, 1991b) these five stages were treated as three (namely, predict, observe and explain), and the cognitive involvement of students at each stage was measured quantitatively. The present study adds to the fundamental understanding of these patterns of interactions (sections 4.1 and 5.1).

Following are the interpretative accounts of students' patterns of interaction (section 1.2 question 3) at each stage, based on what students did, and the results of data analysis that were common to both MBLs.

The first of the five stages often engaged students in an extended discussion in order to settle on an interpretation and/or execution of the task. While not usually involving the computer display (such as by viewing a previous graph if the task so required), this stage focused students' thinking forward to the anticipated display, and students usually made their predictions in the form of screen graphs. The requirement to make a prediction also often forced students to consider their present conceptions and commit themselves to a prediction. Looking at, feeling and manipulating the apparatus appeared to aid them to conceptualise the problem. Understanding, interpreting and predicting were complementary processes. Students knew that their interpretation of the task directly affected their prediction. On a few occasions students had a firm idea of what the prediction should be, and modified their understanding of the task accordingly. For example, if they knew that a displacement graph should start and end with zero displacement, then they interpreted the execution of the written task accordingly (section 5.4.2). Sometimes each student in the dyad settled for a different interpretation, and of course different corresponding predictions, in which case they often conducted an experiment for each task interpretation. With the fast data collection relating to kinematics, conducting two experiments took little time. Since many of the tasks were open to multiple interpretations or experimental procedures, the students had the freedom to create their own experiments, which allowed them a feeling of autonomy in the laboratory. Student-oriented tasks such as these have been found to stimulate collaborative group activities (Crawford, Krajcik, & Marx, 1999). As students progressed from task to task, the more they referred to the results of earlier experiments, to assist in making predictions about new tasks. For example, Sue applied the results of an earlier task involving a cyclist riding up a hill and returning to the start, to predict the motion graph of a batsman making two runs (section 5.4.2.1)

Students treated the second stage of setting up the experiment as a shared activity, exchanging places periodically between working at the keyboard to set up the screen display, and manipulating the equipment. Students in all the videotaped dyads appeared to share these activities equally. Usually this was done by general agreement, taking turns at the keyboard and experiment bench. Where one felt he/she could manipulate his/her partner's equipment better, or had an inspirational idea, they exchanged places. The only report known from the literature of shared manipulation come not from MBL studies, but from students using simulation programs. For example, McLellan (1994) reported that in 17 of 19 dyads, one partner interacted substantially more with the sole manipulable apparatus (the keyboard) than did the other partner. Results from the present study suggest that when there are two or three students in an MBL they share involvement at two active sites (the keyboard and the bench top apparatus), sufficiently separated that the students are not crowded together.

With thermal physics the first two stages (figure 4.1) were closely linked, and this is likely to be the case with any experiment that uses sensors attached to experimental apparatus. (In the case of kinematics there was no additional experimental apparatus, the sensor being held in the hand.) Often students interpreted the task and made their predictions coincidently with setting up the apparatus. One interpretation would be that the process of fitting the sensor and fiddling with the equipment helped students conceptualise the task, and predict the graph.

In the third stage, collecting data and observing, the students' gaze and topic of discussion crossed back and forth between the experiment and the developing graph. The range of student activities during this data logging stage was determined by the length of the experiment. For experiments lasting a few minutes, the activities included: touching the apparatus and making adjustments to produce screen feedback; viewing and assessing the quality of the screen graph; and active discussion within the dyad, which merged into the fourth and fifth stages, analysis and explanation. It is important to note that observation of the developing graph alongside the experiment (often accompanied by analysis and explanation) is only possible with real-time data conversion and display. This contrasts with Calculator-based laboratories (CBLs) which do not in general have a real-time display. Further, activities in this stage support two claims associated with the real-time display, namely that it increases the efficient use of class time, and it frees students to integrate ideas (Linn & Songer, 1991b). The students' actions in this stage were purposeful in that they were directed to assessing the quality of the graph, and to juxtaposing their prior understanding and predictions against the evidence unfolding on the display. Seeing whether predictions were accurate was a way for students to test their understandings. If the display showed up a flaw in their procedure they repeated the experiment until data were acceptable.

During stage 4, analysing the graph, the interactions between the two students, and students and the screen become most important. Kelly and Crawford (1996) described 12 different student-display interactions, grouped into two pathways by which the display entered students' conversations. The present study identified many of these 12 student-display interactions. In the first pathway, the display was viewed as a member of the group providing information. In the second pathway, the student processed information from the display, and then used the display to support an argument or explanation. This study found that the experimental apparatus and POE worksheets also entered dialogue in the same manner as did the display, albeit less frequently (see Figure 4.2). Supplementary printed tables and diagrams in the POE worksheets, and characteristics of the experimental apparatus, provided information and were appealed to for support of an argument. At times students interacted with all three – display, supplementary source materials, and apparatus – synergistically. When students obtain information from three sources, create their explanations, and relate these back to the sources, then these interactions can be expected to support cognitive changes.

In the final stage of explaining and recording, students frequently read their conclusions aloud as they wrote them. Reading aloud is consistent with the interpretation that the students were helped in a number of ways: as a self-check that their explanations were comprehensible; as an aid to clarify their own thinking; to assert their explanation to their partner; or to seek confirmatory approval from their partner. For longer experiments stages 3 to 5 were closely linked in that students combined observations, analysis and explanations within a few turns of speech, and iterated through this cycle as the graph evolved (sections 4.1.1.2 and 5.1.1.4).

During data collection, analysis and interpretation the students also interacted with other dyads, the teacher, and an assemblage of prior concepts, earlier experiment results and previously concluded theory. This study not only found supporting evidence for the descriptions of students' interactions with computer representations as reported by Kelly and Crawford, it extended the description of network interactions to encompass all the other actors in the MBL.

Teachers as facilitators in a constructivist oriented MBL can benefit from this description of the network relationships in two ways. The first relates to the worksheets prepared by the teacher. The network of actors shows that a constructivist MBL constitutes more than a laboratory with computers, individual students and teacher. Other actors include the students working as dyads (or triads), other groups, and the written materials (the boxes in Figure 4.2). With reference to the written materials, well designed worksheets that promote student interactions and provide rich additional resource materials evidently promote network interactions (the arrows in Figure 4.2).

The second way by which the network description (Figures 4.1 and 5.2) can benefit teachers, is in revealing how students interact at different stages of a task. With this knowledge the teacher is better equipped to stimulate these interactions as he/she circulates in the laboratory, such as by asking questions appropriate to each stage, making students aware of unused resources, and encouraging students to follow the POE format and not omit any of the steps.

This section has contributed to a better understanding of how constructivism relates to an MBL that uses a POE strategy, and provides direction for teachers who may be making the difficult change from other teaching philosophies and styles (Clark & Jackson, 1998).

6.2 ASSERTIONS COMMON TO THERMAL PHYSICS AND KINEMATICS

6.2.1 Students and the computer display

In answer to the question (section 1.2, question 4), how are students' negotiations of new understandings mediated by the computer display, this section focuses on the students: their perceptions of the display, their level of mental engagement with the display, their discursive practices directed at interpreting graphs, and how the display aided them as a memory support.

6.2.1.1 The role of the display

Understanding students' perceptions of the display may enable the teacher to utilise its characteristics in ways that learners may not take advantage of themselves. The question about students' perceptions of the display was prompted by Kozma's advice, "the extent to which objects [display graphs] refer to other domains [such as the experimental apparatus], and thus serve as symbols, should be explicitly addressed in research with symbolic environments" (Kozma, 1991, p. 206). There have been few reports of studies that have explored how students view the computer display. In an analysis of students' discourse, Kelly and Crawford (1996) described the display as a silent member of the group, providing unique data, which the other group members interpreted, processed, and linked back to the display. They also gave examples in which students made direct associations between the display and the bench top experiment, and the display and associated physics concepts. The present research supports these observations, though described in different terms.

As students viewed the display their dialogue, gestures, or later written POE notes, showed that they viewed it predominantly as representing the adjoining bench top experiment. As the graph developed, the display became the primary focus of students' attention, and the experimental apparatus secondary. It seemed that Taylor's (1987) application of a statement by Ivins Jr. applied: "The accepted report of an event [in this case the display] is of greater importance than the event [the experiment on the bench], for what we think about and act upon is the symbolic report and not the concrete event itself" (p. 202). The display made visible phenomena that could not be seen in the experiment, such as temperature changes and heat flow, and abstract concepts such as rates of change and directions associated with vector quantities. These powerful transforming attributes of the computer were factors that helped students maintain attention, as also reported by Clark and Jackson (1998). Students were relieved of the boredom of not having to draw graphs by hand, as has been reported previously (for example, Mokros & Tinker, 1987; Stein et al., 1990), and which enabled them to repeat experiments quickly or move on to new tasks.

Students linked the display with stimulus materials provided in their worksheets, such as data tables, formulae, and diagrams. Occasionally the display reminded students of a similar graph they had seen in another context, such as on an instrument in a hospital ward, and they considered what possible connections there may have been between the two.

A few students operated on the screen graph as an object in its own right, subjecting it to detailed mathematical analysis, such as calculating slopes and areas under curves. In doing this they temporarily sidelined the bench top apparatus, made their lengthy calculations, then applied the results back to the experiment or worksheets. Students who did this had more advanced mathematical skills. This suggests that tasks which require complex calculations should take into account the students' mathematical level.

Previous assertions made about the role of the display (Assertions T1 and K1 in sections 4.2.1.2 and 5.2.1.2) are here combined into a statement about the representational nature of the display. This and the following assertions in this chapter apply to both thermal physics and kinematics MBLs.

> Assertion 1. Students view the display: (a) predominantly, as representing the experimental phenomena; also, (b) as relating directly to the original written task, or associated stimulus materials supplied in worksheets; and (c) when the nature of display lends itself to such a treatment, as a graph in its own right.

6.2.1.2 Confidence in the display

Students expressed confidence in the accuracy and reliability of the display data based on the technology, and this is consistent with other findings (Clark & Jackson, 1998). This extended to accepting graphs that presented results at odds with their predictions (discrepant events).

This is not to say that students accepted all graphs. Students were critical of poorly selected scales and the general appearance of graphs, specially when the results showed they had mismanaged their experimental procedures. In such cases they repeated experiments until satisfied with the results. One study by Nachmias and Linn (Nachmias & Linn, 1987) reported that students sometimes accept graphs uncritically. They found that students inexperienced with temperature graphs failed to recognise graph errors caused by inappropriate hardware and software settings. Students tended "to evaluate computer-presented graphs uncritically much as they assess textbook-presented graphs and other scientific information" (p. 502). Such a study, based as it was on the quality of software and hardware at the time, would not be appropriate today.

All students were able to make sense of the screen graphs at a basic level without difficulty and to make qualitative estimations and comparisons. The uncluttered appearance of the MBL display would appear to contrast with simulation screens that generally contain more complex features (Rieber et al., 1996), and which make it more difficult for students to coordinate their talk and attribute the same meanings to screen features to which they point (Roth et al., 1996).

Students made allowance for irregularities in graph lines caused by sensor and human errors. Student frustration caused by poor results was very low, but reports from other laboratory studies show that this has not always been the case. Irritation due to 'noisy' data and erratic graphs, a product of poor experimental techniques, has a history of turning students and teachers against MBL methods (Clark & Jackson, 1998; Russell, 1991a).

In summary the assertion is made (cf. Assertions T5 and K4):

> Assertion 2: Students (a) express confidence in the accuracy of the display, based on the technology, and (b) are able to distinguish between graphs that portray poor quality data (which graphs they repeat), and good quality data, even when the graph presents results contrary to their predictions.

6.2.1.3 Level of student-display interactions

Viewing the display and associating it with an experiment does not necessarily imply students' meaningful involvement with or understanding of the physical phenomena. Students who do only sufficient to fulfill basic task requirements can be said to take a surface approach. They do not reflect on the purpose of tasks and fail to associate the details with other meaningful schemata. Meaningful involvement suggests a student reflects on an experiment, and builds on understanding from earlier experiments to construct new knowledge. This deep approach to learning is characterised by intrinsic motivation, and actively manipulating information with a focus on understanding and integrating knowledge. Characteristics of surface and deep approaches, as described by Chin and Brown (2000), that matched instances of dialogue in student-display interactions were used to assess the level of student-display interactions. These are listed in Table 4.1 (section 4.3).

Of other reports of students' interactions with the display, none has been sighted that measured their level of mental engagement. The report by Kelly and Crawford (1996) of the use of computer representations in students' conversations included evidence that students in their MBL operated at a deep level. Of the 12 ways in which they described the computer entering a conversation, when matched with descriptions of deep involvement in the present study (Table 4.1), 7 required that students think deeply. Kelly and Crawford found students used the display to make a case, construct meaning, make a claim, predict, demonstrate a key point, provide clarification, and highlight apparent anomalies. These descriptions reflect students' operating at a deep level. In the present study each of the students selected for detailed videotaping operated at some time at a deep level. While there was no direct evidence that all the non-selected groups for detailed videotaping applied deep mental processes, their written POE explanations suggest that the majority did. Those who took a deep approach were taken to be intrinsically motivated, actively manipulating data with a focus on understanding and integrating knowledge.

In summary, the assertion is made (cf. Assertions T2, T3, K2 and K3):

> <u>Assertion 3</u>: During student-display interactions, while students' activities ranged from fulfilling basic requirements to deep level cognitive processing, the dyads completed the majority of their tasks at a deep level of mental engagement. The permanent nature of the display supported this level of involvement.

This last sentence is added because students needed time to elicit meaning from the graphs. It seemed that the longer students examined the display, the more information they extracted and processed. The interpretation of graphs and creating relationships between graphs and task problems required extended references to the display to the extent that, in the opinion of Taylor (1987), the display became more real than the experiment itself.

The capacity of the display to support deep mental involvement suggests that the display's role transcends that of another laboratory tool, such as a micrometer or a voltmeter. Thornton and Sokoloff (1990), in their study of groups using a guided-discovery approach in a kinematics MBL, suggested that the value of the display was embedded in its combination with curricular materials.

> The tools, however, are not enough. Preliminary evidence shows that while the use of the MBL tools to do traditional physics experiments may increase the students' interest, such activities *do not* necessarily improve student understanding of fundamental physics concepts of [kinematics]. These gains in learning physics concepts appear to be produced by the combination of the tools *and* the appropriate curricular materials (p. 865, emphasis in the original).

In the present study it has been shown that the display is part of a network, and all the actors function in an inter-relationship that shapes students' conceptual development. This suggests that the last sentence of the statement above by Thornton and Sokoloff be expanded to include all the actors in the MBL.

6.2.1.4 Student discourse and graph interpretation

When Clark and Jackson (1998) wrote in their conclusion to a year-long study of a conceptual physics classroom "we need to come to a better understanding of how constructivism fits with the use of computer assisted data collection. . . . we need to study how students make connections between MBL activities and the physical phenomena" (p. 32), they acknowledged the meagre professional literature that sheds light on these questions. Kelly and Crawford (1996) conducted one of the few studies that addressed this question in a physics MBL. They described specifically the role of the display in student conversation. The present study includes the broader community of actors in the students' dialogue.

To give an example from the present study (discussed fully in section 4.4.2.1), consider the task in which students had to predict which of four metal samples would be best suited to make a saucepan. John and David selected stainless steel, based on their shared knowledge of the characteristics of each metal. After completing the experiment, which measured the thermal conductivities of the metals, they were surprised to see graphs that showed copper and aluminium conducted best, followed by iron, and stainless steel conducted the worst. This led to a sustained discussion to make sense of the unexpected result. David and John drew on their knowledge of chemistry, general knowledge, worksheet data tables, and even weighed the metals in their hands to compare their densities. After resolving several different opinions and making a number of erasures on their POE notes, they arrived at a common explanation consistent with the display graphs. The majority of students had similar experiences. Some believed they could show in the graphs evidence that stainless steel "retained heat" better than other metals, a result at odds with accepted science, and which they discarded in the course of a later experiment. The task generated much discussion within and between groups. This illustrates a number of activities in the following the assertion (cf. Assertions T7 and K6):

> Assertion 4: Within and between groups, students engage in a broad range of activities linking all actors in the MBL, to create and interpret graphs. These activities include:
>
> - evaluating the display to confirm or disconfirm predictions;
> - theorising, based on personal experience, comparisons of graphs, the results of previous experiments, and worksheet stimulus materials;
> - expressing agreement, disagreement, and self-correction;
> - interactively correcting a partner, counterbalancing opinions, resolving conflicts, and generally scaffolding understanding;
> - trialling ideas, predicting and proposing new experiments;
> - note-taking to crystallise ideas and to maintain a record;
> - crosschecking graphs and techniques with other groups or the teacher; and
> - extended silent meditation of the display, particularly as they formulate the wording of their POE explanations.

Student dialogue and actions linked all of the actors in the laboratory. By means of the above activities, student dyads, the display, experimental apparatus, written POE notes, other groups and the teacher shaped their involvement with and gave meaning to one another. It is important to note also that the interpretation of graphs, formulation of canonically acceptable concepts, and correct resolution of tasks are incremental processes. Many instances were noted of students returning to earlier tasks and making corrections, in the light of their changing understandings that came in later experiments.

The special role of the display in students' dialogue is acknowledged in this next assertion (cf. Assertions T8 and K7):

> Assertion 5. The display serves as a shared resource for joint knowledge construction. With direct reference to the display students:
>
> - test and verify or reject existing beliefs;
> - identify patterns and trends;
> - analyse graphs, by dividing them into small sections for individual analysis; and

- use the screen as a working diagram against which they can hold straight edges, read data; measure maxima, minima and changes, estimate ratios, calculate gradients and areas under curves; compare and contrast features of multiple or overlaid graphs, extrapolate trends, and interpolate data.

The display acted as the principal focal point for group cooperation. Students touched the screen with fingers, marked it with felt pens, held straight edges against the face, and made handwritten copies for permanent records.

Many examples that were analysed in chapters 4 and 5 showed how students changed their formerly held concepts of heat and motion to more scientifically acceptable views. The purpose of this study was not to categorise or quantify students' conceptions and conceptual changes; rather, it was to study student interactions in a physics MBL, and how the materials and strategies supported (or constrained) student understanding. Conceptual change theory (CCM) developed in the early 1980s (Duit & Treagust, 1998) suggested there were four conditions that fostered conceptual change. There must be dissatisfaction with present conceptions, and new conceptions must be intelligible, plausible, and fruitful. CCM has been used fruitfully in science education research and physics instruction (Tao & Gunstone, 1999; Thorley & Stofflett, 1996). In recent times CCM has taken into account the important roles of affective (motivational), social and contextual factors in the classroom. In their critique of CCM, Duit and Treagust (1998) observed that conceptual change has to be embedded in conceptual change supporting conditions. The analysis of student dialogue gave evidence of students being given opportunities to predict, confront discrepant results, exchange ideas, and scaffold their knowledge. In summary, the assertion is made (cf. Assertions T6 and K5):

> <u>Assertion 6.</u> Learning conditions in the MBL in this study are conducive to fostering conceptual change, the conditions being: graphic evidence to engender dissatisfaction with prior conceptions; opportunities to construct new conceptions that are seen to be intelligible, plausible and fruitful; and an atmosphere that is motivationally and socially conducive to constructing new understandings.

Insofar as students used worksheets based on a POE format (White & Gunstone, 1992) consistent with a constructivist view of learning, strategies in this MBL were designed intentionally to foster change-supporting conditions. The predict requirement forced students to express their prior beliefs, observing the display confronted students with conflict (and confirmation), and writing explanations presented students with opportunities to construct new conceptions consistent with the graphic evidence. Variations of these strategies have been mooted or implemented in a wide range of school laboratories in an effort to improve student learning (Blakely, 2000; Colburn, 2000; Shiland, 1999; Voogt, Gorokovatschke, & Pourycheva, 2000).

The present study supports the findings reported by Clark and Jackson (1998), that those features of an MBL which were conducive to conceptual change included: students trusting the technology (making the results plausible), seeing results in real time (making the results intelligible), and being able to explain new ideas based on what they actually see (making the results fruitful). The findings are also consistent with the conclusion by Svec (1995), who conducted a quantitative study of the relative effectiveness of traditional laboratory methods and MBL for engendering conceptual change in students studying an introductory undergraduate kinematics course: "Activities which emphasize qualitative understanding, requiring written explanations, cooperative learning, eliciting and addressing students' prior knowledge and employing the learning cycle are more effective for engendering conceptual change" (p. 22).

For both thermal physics and kinematics the POE requirements kept students on task, and while they felt these were demanding, all of the students interviewed spoke positively about the benefits they received by having to step through the predict-observe-explain process. Other MBL studies have found also that worksheets, along with the display, supported sustained dialogue (Rogers & Wild, 1994; Solomon et al., 1991).

6.2.1.5 The display as a memory support

Many claims have been made that strategies for using MBLs and graph displays support students' working memories (Linn et al., 1987; Linn & Songer, 1991b). In this context, the characteristics of working memory refer to students' (a) concurrent storage and processing of information, (b) maintenance of information over time, and (c) level of alertness, in combination or until some action can be initiated (Pennington et al., 1996).

It seems an MBL supports working memory by reason of (a) its real-time data logging and processing, and (b) its permanent graph display. When selecting an MBL environment for thermal physics experiments, Linn and Songer (1991b) asserted that "real-time data collection provides memory support and frees the student to concentrate on integrating ideas" (p. 889). Their conclusion reflects earlier research (Linn et al., 1987) in a kinematics MBL, that reported "the mechanisms governing success of MBL are not yet clear. We suspect that the memory support available in this environment facilitates learning" (p. 252). Quantitative kinematics tasks are particularly demanding on students' information processing, requiring skills of graph analysis, such as measuring, calculating, comparing and interpreting motion graphs. However, in both branches of physics the evidence of this study seemed to give strong support to Nakhleh and Krajcik (1994), who suggested that MBL students' short-term memories were freed to reflect on their activities while the screen retained the graphic data. "In a real sense, the computer seems to be functioning as an auxiliary memory . . . information [on the display] was not transient" (1991, p. 24).

There is another aspect to the memory support idea that appeared in the present study, and that is the ability of students to recall from long-term memory, hours or days after the event, the shape of a graph and its associated experimental phenomena. Such graph shapes and their associated experimental phenomena are templates, "stereotypic sequences of activities that are used repetitively in solving problems" (Linn et al., 1987, p. 247). Many examples appeared in the analyses of chapters 4 and 5 which showed graph shapes became sufficiently imprinted in students' minds as to be retrievable in later MBL sessions. It is important to note that when recalling a graph shape, students always seemed to retain the link with its associated experiment. Adams and Shrum (1990) claimed that students "had a 'mind's eye' picture of laboratory events not available to students conducting laboratory exercises in the conventional manner. They could realistically remember what the line on a graph did when they heated water" (pp. 783-784). In the present study, students used their memories of graph shapes to construct or reconstruct understandings of later graph displays and associated experiments. The worksheet tasks were structured sequentially to facilitate this process of scaffolding template building.

In summary the assertion is made (cf. Assertion K8):

> Assertion 7: The display supports students' short term working memories, freeing them to reflect on their activities while the screen retained the graphic data. Students also retain templates of graphs with associated experiments in long-term memory.

6.2.2 Teacher interactions with students

This section discusses teacher-student interactions, in response to the third study outcome (section 1.2), to provide specific details of how the teacher acts to facilitate learning.

The research literature on MBLs, and in recent years constructivist MBLs, is almost wholly directed towards student learning processes and outcomes. In addition, many science educators have described desirable teacher activities for constructivist science classrooms and laboratories (for example, Colburn, 2000; Minstrell & Stimpson, 1992; Novodvorsky, 1997; Shiland, 1999), and a small number of studies of teachers in naturalistic science classroom settings have been published (for example, Maor & Taylor, 1995; Roth, McRobbie, Lucas, & Boutonné, 1997; Tobin et al., 1997). However, no research has been sighted of teacher practices in an MBL. The characteristics of the MBL differ from laboratories using simulations, multimedia and other computer-related technologies, and so are the teaching activities. This section presents the personal reflections of the teacher as he interacted with students and how these experiences link with the literature.

The first ten minutes of each lesson were used to review results from the former lesson and to describe the experiment materials for the current lesson. Once the experiments began, the teacher's immediate role was that of classroom manager. He answered procedural questions about computer hardware and software, technical aspects of the experiments, and procedural aspects of the tasks. These questions were more frequent during the first of the four lessons of each of kinematics and thermal physics, indicating that students took time to settle in to their tasks. Reports from some MBLs have shown that when the teacher and/or students have been unfamiliar with the MBL materials, management issues dominated over the teacher's role as facilitator and levels of frustration for both teacher and students increased. This resulted in decreased student motivation, even the teacher's discarding MBL technology (Clark & Jackson, 1998; Roth et al., 1996; Russell, 1991a).

The teacher's principal role was that of facilitator, now described briefly, and which has been illustrated in the dialogue analysis of sections 4.4.3 and 5.4.4. On approaching a group he generally paused to determine what the group was doing, and the stage of their current task, by reading their POE notes. After that he asked questions about the display, their note-taking, what they were trying to do, what they had predicted, and what they thought of their results. He asked about discrepancies with their predictions, the results obtained by other dyads, relationships with previous experiments, and their explanations. At times he feigned ignorance of some aspect of their activities, and students responded as though they were the experts teaching the teacher. He answered questions with questions, asked "what if" questions, and simply echoed students comments. At times he played the devil's advocate to challenge students' thinking. He used "wait time" to elicit responses. The teacher's motive was to stimulate student dyads to express their ideas, juxtapose these with the display, and scaffold new understandings. On many occasions these questions prompted students to express themselves beyond what they might have done otherwise. This prompts the next assertion (cf. Assertions T9 and K9):

> Assertion 8. When the teacher asked probing questions, they often stimulated deeply processed responses linked to graph features and the experimental phenomena.

The teacher's dialogue was consistent with advice from the literature. For example, Colburn (2000) advised teachers applying constructivist ideas in a science classroom to use a questioning strategy that encouraged students to reveal what they were thinking, and to put students into situations where groups debate, discuss, research, and share. However, as revealed in the videotapes, at times the teacher misinterpreted what students were doing or saying, and consequently his questions distracted and confused students, while at other times he drifted into a transmissionist monologue. On the latter occasions students actually benefited little, because the points he explained were beyond their level of physics. His tendency to do this was not surprising, as the teacher tended to do this during the pilot study (Russell et al., 1999), and research suggests that teachers may take a number of years to conform to the constructivist beliefs they have adopted (Colburn, 2000; Tobin, 1991).

Students sometimes asked the teacher directly what the answers were. Rather than confirm or discredit interpretations, he tried to refer students to untapped resource material in their worksheets, results from earlier experiments, or to another group that he knew had particular success with the task. When their data or procedures were poor, he recommended students discuss their results with a group that he knew had model results. He found that responding to such queries was an art that took time to learn. "A challenge for constructivist teachers lies in helping learners construct these ideas without violating constructivist learning principles" (Matthews, 1997, p. 13).

6.3 HOW MATERIALS AND STRATEGIES SUPPORT STUDENT UNDERSTANDING

This section contains a partial response to the second research question (section 1.2), how do the materials and teaching strategies support (or constrain) student understanding, also alluded to in the foregoing discussion.

6.3.1 Hardware and software

The MBL hardware and software were produced locally by the teacher (Russell, 1991a; Russell, 1991b) based on his research into and concern for the slow teacher uptake of computers in science laboratories.

> The interface was designed so that teachers, the majority of whom have no technical expertise, would not be dependent on the manual for science laboratory experiments. . . . Thus the computer with interface attached was intended to be no more difficult to use than any other laboratory instrument. Teachers required software that was easy-to-use, error free, able to provide reliable results, and usable for a variety of applications . . . menu-driven . . . [with] screen displays attractive but not cluttered. (Russell, 1991a, pp. 60-63)

These concerns for teacher uptake subsequently simplified student uptake, which has not always been the case. When students failed to master the software environment (MacIsaac, 1995; Roth et al., 1996), the hardware was prone to record spurious data (MacIsaac, 1995; MacIsaac & Hämäläinen, 2002), or "the interface . . . was not at all intuitive for the teacher or the students" (Clark & Jackson, 1998, p. 15). The teacher also manufactured collateral apparatus in the school's manual arts department, that could be linked with sensors and require minimal manual dexterity to assemble. Attention to these details is necessary to avoid student frustration and allow them to concentrate on the phenomena being investigated (Clark & Jackson, 1998). The strategy of establishing up to 12 computer work stations, with friendship groups of dyads and triads promoted cooperative learning. These group sizes allowed each student sufficient bench space for experimenting, a share in manipulating the equipment, and a clear view of the screen.

6.3.2 The POE worksheets

The decision to use worksheets was in part a response to the consistent mention in the literature that students need direction to focus on laboratory activities and to stimulate social interaction (Linn & Songer, 1991b; McLellan, 1994; Rogers & Wild, 1994; Solomon et al., 1991). The POE format described by White and Gunstone (White & Gunstone, 1992) and used to advantage by others (for example, Linn & Songer, 1991b; Tao & Gunstone, 1997b) is ideally suited to the MBL environment. POE tasks require that students understand the nature of the event, predict an outcome and justify it. Prediction requires students to select principles or recall to mind prior examples that may illuminate the situation at hand. The justification requirement discourages guessing. Students then describe what they see happen, and reconcile any conflict between their prediction and the outcome. The cycle is then repeated either by proceeding to the next required prediction, or the student setting his or her own.

The demands of the POE procedures were exacting. Mark's interview statement (AS2071099) is worth repeating:

> Because if you are left to do it on your own, you think: "Oh blow the predictions, just go ahead and do it and fill all of that out later." Whereas with this [the POE notes to be completed] you are forced to make a prediction before you start and then see what happens, and try to figure out why it happens.

The POE task sheets were supplemented with additional data in the form of an introductory list of new terms, and qualitative and quantitative homework problems to follow each day's activities. Tabular data from the homework problems were available for students to draw on in future MBLs.

As both a framework and strategy, the POE worksheets acted as a clothesline, as it were, on which students could hang their activities – discussions, planning, argumentation, conjectures and so forth – in an atmosphere conducive to students making conceptual changes (Tao & Gunstone, 1997b). The analyses of dialogue presented many examples of how students' thinking was challenged by the tasks, how they re-constructed concepts, and how they used these fruitfully to explain further phenomena.

6.3.3 MBL characteristics that supports student centred learning

Science teaching involves trying to help students change their beliefs to be more in line with those accepted by the scientific community. These may be beliefs that are not even apparent to themselves, much less to the teacher. A framework to facilitate students to change their minds involves helping students (a) clarify understanding of their own ideas and (b) confront problems with their beliefs, and (c) presenting students with alternative concepts that work better for them personally (Colburn, 2000; Posner et al., 1982). The diagram of patterns of interaction in Figure 4.2 is referred to in this discussion, as it includes all the actors and relationships in the MBL. Using this framework and the diagram, it is possible to see how the strategies and materials used in the MBL support student understanding.

Students control their activities and discourse. The network diagram shows that the students are at the centre of all interactions. They are also in control of all of their actions and dialogue. There are no expected answers, they are only answerable to themselves. Individuals are free to negotiate with other students to clarify ideas. The teacher exists only in a consultative role. (The management role is not being considered at this point.) This is in contrast to a traditional teacher-centred laboratory.

Often there are no unequal power relationships. In the MBL, students take control of their learning, and the teacher is sidelined some of the time. Power is also shared across the other actors – the POE worksheets by reason of their requirements, other dyads, phenomena associated with the experiment, the symbols on the display, the history of recent experiments and so forth – which bring their influence to bear on the students. The teacher tries not to deflect students from their normal behaviour. Rather, he/she tries to build a rapport with students. The classroom climate is different from that of the traditional laboratory in which power is often shared unequally by the authority of the teacher and prescriptive task requirements. Issues of classroom climate and power structures are important to engender conceptual change supporting conditions (Duit & Treagust, 1998).

Students enroll the support of other actors to make claims. In making a claim (a prediction or explanation), the student marshals the support of other actors/resources to gain support. Initially these are only the POE task and prior concepts. As the laboratory proceeds the network expands to include the experimental phenomena and display, which may present data that conflict with the claims, resulting in a new or adjusted claim. The claims at each stage are socially and temporally situated. The teacher enters the network in a way different to the other actors, in that he/she does not input information. The teacher sensitises students to the availability of unused information in the network, and by questioning stimulates students to operate at a deeper cognitive level than they might otherwise function.

The teacher is advantaged as an onlooker of students' activities. By intentionally not influencing students' thinking, the teacher does all he/she can to understand the world of the students as they see it. The teacher gets to know what students are thinking when they express themselves, and by reading their predictive graphs (Greca & Moreira, 2000) and written explanations. This knowledge is important to the teacher. He/she uses it to guide questions, to encourage inter-dyad discourse, for lessons following the MBLs, and for writing future laboratory tasks that may challenge their thinking.

6.4 INTERPRETATIONS OF LEARNING IN THE MBL

This section presents the personal reflections of the author, as both teacher and researcher, on his physics instruction in the MBL (section 1.2, outcome 1).

6.4.1 The teacher's interpretation of learning in the MBL

The MBL provides a unique opportunity for the teacher to interact with individual students. The teacher found the MBL setting, combining all elements of Figure 4.2, differed to other laboratories he had experienced. The presence of all these elements (in particular the display and POE notes) as discussion-generators in close physical proximity seemed to stimulate conversation.

The teacher was able to follow students' thinking, learn why they held certain beliefs, and track changes in their conceptual development, as he listened to or entered their conversations. This calls for examples. On days 1 and 2 one dyad believed that iron and steel "retained their heat" better than copper and aluminium (section 4.2.1.1), and pointed to evidence of this in certain graphs. This was the experiment in which four metal rods were stood in a bath of hot water. The top ends of the copper and aluminium rods heated very quickly, then after awhile their temperatures started to drop. Meanwhile the temperatures at the top end of the steel and iron were still rising, very slowly. The students interpreted the still-rising steel and iron temperature curves as an indication that the metals were retaining heat, and the falling curves for copper and aluminium suggested they were not retaining heat, an interpretation that would never have occurred to the teacher. Yet by day 4 neither student continued to use this phrase, but instead they explained this experiment canonically in terms of thermal conductivities and heat capacities. As a second example, Cate and Sue grappled at length with the problem of a cyclist riding up a hill, pausing, then returning to the starting point. They had to imitate the cyclist by pushing a hand-held wheel back and forth on the bench top. The question was, should they turn their hand-held wheel around 180 degrees for the return trip, or should they roll their wheel backwards? They eventually settled on two conclusions: one, to follow the practice of cyclists and turn the hand-held wheel (the bicycle) 180 degrees (because cyclists don't ride in reverse); and two, roll the wheel backwards, because that would be the practice of a physicist (to maintain a direction convention). The teacher himself had not previously considered the practical issue of turning/not turning the wheel around, and he used this knowledge in later lessons. As a third example, the dialogue analysed in detail in section 4.4.3.1 gave an extended example of student-teacher interactions about graph interpretations not possible outside of the MBL.

The teacher learned about the capabilities of individuals as he visited dyads. Jane, academic rank 17th in her class (n=29), took the initiative with POE tasks and demonstrated an excellent grasp of kinematics, as compared with her quiet partner Tony, ranked 1st. Joel outwardly appeared retiring, and usually contributed little to class discussions, but in the MBL the teacher was deeply impressed with his insightful explanations. In later months the teacher used these observations to guide Jane and Joel through the physics course.

The nature of the teacher's role and interactions with students in both thermal physics and kinematics was fundamentally the same. This did not surprise the teacher, since most of his questions involved the display and the predict-observe-explain tasks and format that were common to both. Only the principles of physics and the specific experiments changed. In actuality the teacher's experiences with students in the kinematics MBL differed in that they were six months younger, had just begun their physics course, had no prior experience in an MBL, and were almost double in number to the thermal physics class. These differences were not intrinsically linked to the particular domain of physics. How aspects of the different physics domains differed and the implications for the teacher are discussed later.

How might the lessons have differed without using MBL technology (but still using constructivist principles)? The question is problematic, but the teacher offers his personal reflections, and relates independent support from the literature. If the alternative laboratory used electronic technology for data collection, the essential difference would be its lack of a real time graph display. Without real-time graphing:

- Students would find the laboratory less interesting (or as many said in interviews "boring") and less motivational (Clark & Jackson, 1998; Brasell, 1987).
- The link between experiment and results would be less meaningful. Brasell found that a delayed time display decreased students' comprehension of distance and velocity graphs (1987). Krajcik (1991) suggested that the effectiveness of MBL and level of concept richness are connected to the instructional sequence surrounding the MBL activity. The close association between experiment and display helps students learn graph "templates" (Linn et al., 1987) on which to base the understanding of future graphs.

- Frequent repetitions to confirm, compare, or create “what if” graphs for display would not be possible. Solway (1994) reflects the same opinion: “‘What if, . . .’ That phrase is music to a science teacher, it means the students are engaged and thinking” (p. 2).

- Processing data, such as by calculating velocities from displacement data, would be very time consuming.

- Data are less meaningful when presented in non-graphic form. Svec (1995) showed that motion problems were better understood when presented graphically.

- Accepting that physicists prefer data in graph form, the time taken for students to hand-draw graphs would be greater by an order of 2 or 3 (that is, 10 to 100 times longer than the experiment). This has a negative consequence for concept development. The graphing capabilities of MBL have been found to be more effective in engendering conceptual change in students than a traditional laboratory (Stuessy & Rowland, 1989; Svec, 1995). On the other hand Adams and Shrum recommended that hand-graphing exercises should be maintained if the teacher’s purpose is to teach graph construction (1990).

- The teacher and other groups would not be able to interact as effectively with the dyad without the display as actor mediating their dialogue. This would curtail the social construction of knowledge.

If the non-MBL did not use electronic data logging, students’ experiences would be even more curtailed. In addition to the seven points above:

- Data logging would be very slow, meaning that fewer experiments would be conducted in the time. Stein, Nachmias and Friedler (1990) found that students in an ordinary laboratory took twice the time as in an MBL, and they suggested the additional time could be used for reflection and substantive discussion.

- Students would be less confident in the accuracy of their results, and hence the results may be less convincing if they differ from students’ expectations. Clark and Jackson found that MBL data was perceived by students as being more accurate and gave them more confidence in the results they were seeing (Clark & Jackson, 1998).

- The variety of possible experiments would be curtailed severely, and consequently the variety of tasks.

How might the teacher's role in the MBL have differed from his role in the traditional laboratory? Firstly, in the MBL the teacher was freed from moment-by-moment supervision of the class. Students were familiar with the POE approach, and the nature of the tasks meant that students controlled their own experiments and worked autonomously. For this reason the teacher felt the demands on himself as teacher were less stressful than in a traditional laboratory, in which the teacher took responsibility for giving direct instruction. Secondly, under these conditions the student-teacher relationship changed from teacher as supervisor to teacher supporting enquiry. This was reflected in the teacher's conversation that changed from giving directions to asking questions.

The majority of students responded positively to the teacher acting in the role of facilitator instead of teacher. As the teacher circulated from group to group, some students boasted about their experimental results or their predictive abilities. Occasionally dyads asked the teacher to adjudicate between their conflicting results or explanations. Other dyads just went on with their work. Dyads who had met an impasse sought him out for assistance. The teacher felt that a few students would have preferred to be told answers directly. He was aware that a constructivist approach is not best received by all students (Tsai, 1999).

Thus far this section, in reply to the first objective of this research (section 1.2), has painted a picture of how students learn physics in a constructivist MBL. It has described the actors, their relationships and interactions in the laboratory, how students proceed through their tasks, the special roles of the display and the teacher, and has listed many of the techniques they used to construct understandings of physical phenomena. The more detailed descriptions of the processes of student learning were presented in chapters 4 and 5.

6.4.2 The researcher's interpretation of learning in the MBL

The researcher's interpretation of learning in an MBL involves the following steps:

1. Students clarify their present beliefs about the experiment, and express their understanding in the form of a graph (sections 4.1.1.1 and 5.1.1.1).

2. The students conduct an experiment and graph the data. They view the graph as representing the experiment itself, and the graph becomes the focus of their attention (sections 4.2.1.2 and 5.2.1.2).

3. If the observed and predicted graphs differ fundamentally, then the students try to reconcile the inconsistency between the graphs (sections 4.4.2.2 and 5.4.2.2).

4. The students analyse the graph for its meaning, then try to construct a new explanation of the experimental phenomena that would account for the observed graph. To do this the students draw on information, concepts, and persuasive arguments from some/all other actors in the MBL network (Figure 5.4). The construction of new understandings is both personal and social (sections 4.4.2.2 and 5.4.2.2).

5. This process continues until the students arrive at a new explanation that is intelligible, plausible and fruitful as regards explaining the observed graph (sections 4.4.2.2 and 5.4.2.2).

6.5 SUMMARY OF FEATURES COMMON TO THERMAL PHYSICS AND KINEMATICS

The following summary of features common to thermal physics and kinematics has been drawn from sections 6.1 and 6.2. The next section discusses differences between the two areas of physics. The actors in the MBL are shown in the boxes of Figure 6.1.

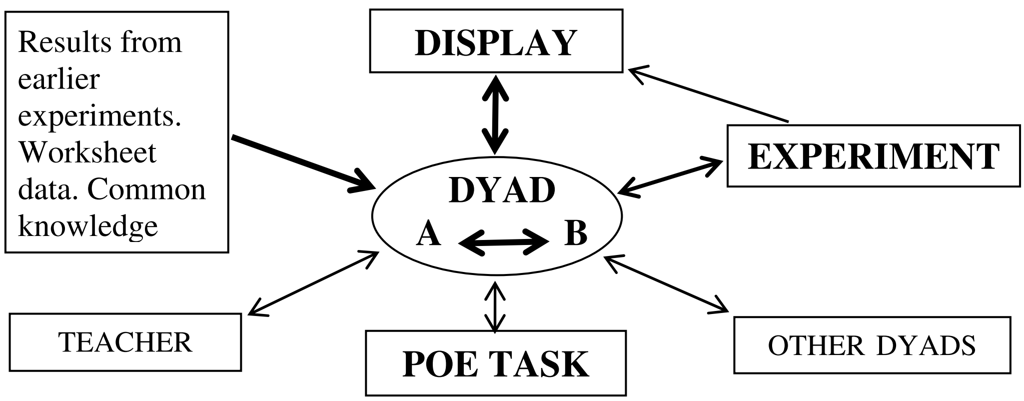


Figure 6.1. Interactions during data collection, analysis and explanation. (This is the same as Figure 4.2, repeated for the convenience of the reader.)

As student dyads address POE tasks they progress through 5 stages: (a) understanding the problem and predicting, (b) setting up and commencing the experiment, (c) collecting data and observing, (d) analysing, and (e) explaining the results. In the first two stages, which often overlap, students conceptualise the task and simulate it as an experiment. The students' dialogue is informed by the written problem, experimental apparatus, and prior knowledge. They express their initial understanding as a written prediction, and set up the experiment. In the next three stages students interact with all the elements in the MBL, but mainly with the display (Figure 6.1).

The thickness of the arrows indicates a judgment made as to the frequency of the flow of information from an actor, or attention given to an actor. Arrows indicate speech, reading, a gesture, viewing, writing, feeling, setting up, or sending as an analog signal. During the last three stages, while observing, analysing and explaining, students collaborate to construct knowledge. For longer experiments students iterate through these stages. During the last three stages the following assertions apply. Table 6.1 is a synthesis of individual assertions discussed in chapters 4 and 5.

Table 6.1

Assertions Common to Kinematics and Thermal Physics MBLs

Students' view of the computer display
Assertion 1. Students view the display: (a) predominantly, as representing the experimental phenomena; also, (b) as relating directly to the original written task, or associated stimulus materials supplied in worksheets; and (c) when the nature of display lends itself to such a treatment, as a graph in its own right.
Assertion 2: Students (a) express confidence in the accuracy of the display, based on the technology, and (b) are able to distinguish between graphs that portray poor quality data (which graphs they repeat), and good quality data, even when the graph presents results contrary to their predictions.
Level of student-display interactions
Assertion 3: During student-display interactions, while students' activities range from fulfilling basic requirements to deep level cognitive processing, the dyads complete the majority of their tasks at a deep level of mental engagement. The permanent nature of the display supports this level of involvement.
Student discourse and graph interpretation
Assertion 4: Within and between groups, students engage in a broad range of activities linking all actors in the MBL, to create and interpret graphs.
Assertion 5: The display serves as a shared resource for joint knowledge construction.
Assertion 6: Learning conditions in the MBL in this study are conducive to fostering conceptual change, the conditions being: graphic evidence to engender dissatisfaction with prior conceptions; opportunities to construct new conceptions that are seen to be intelligible, plausible and fruitful; and an atmosphere that is motivationally and socially conducive to constructing new understandings.
The display as a memory support
Assertion 7: The display supports students' short term working memories, freeing them to reflect on their activities while the screen retains the graphic data. Students also retain templates of graphs with associated experiments in long-term memory.
Teacher interactions with students
Assertion 8. When the teacher asks probing questions, they often stimulate deeply processed responses linked to graph features and experimental phenomena.

6.6 DIFFERENCES BETWEEN THERMAL PHYSICS AND KINEMATICS

The physics of these two areas differs considerably. Motion study graphs focus greater attention on gradients of curves and pattern recognition, whereas temperature graphs often require comparisons between pairs of graphs. Further, motion graphs are generated in seconds, whereas temperature experiments last from two to twenty minutes. By conducting two studies the teacher/researcher aimed to obtain data that would enable him to compare and contrast MBLs in two "different domains of science [that] involve different *kinds* of learning [italics theirs]" (Driver et al., 1994, p. 146). This section discusses the aspects in which the two MBLs differed.

6.6.1 The network relationships

As discussed in section 6.1, the network relationships were similar for both domains of physics, with two exceptions. The first relates to the predicting stage of the network interactions (Figures 4.1 and 5.2). For typical experiments students examined and manipulated the equipment apparatus as an aid to understanding the task. Students drew on tactile feedback (like rolling a wheel or handling bars of metal) and experiential background (such as recalling the properties of different materials) throughout all five stages. However, Type II kinematics experiments (section 5.1.1) involved no experimental apparatus as such. They began with previously generated displacement graphs, from which they predicted velocity and acceleration graphs. In this sense Type II tasks were pseudo-experiments. Interestingly, as they gained experience with these tasks, students explained the shapes of the derived graphs in terms of the bench top experiments that gave rise to the original displacement data. Type II experiments were more suited to students with an advanced mathematical background, because they lent themselves to the interpretation of slopes and areas under curves, both qualitative or quantitative. Despite the differences noted in Type II experiments, no differences were observed in the way that students learned in the laboratory.

The second difference related to the speed of data collection. Thermal physics experiments lasted from 2 to 20 minutes, during which time students recycled through the observing-analysing-explaining stages, sometimes adjusting apparatus and continuously assessing feedback. On the other hand kinematics experiments lasted about 10 seconds, which meant easy repetition of data collection, but retrospective data analysis. These differences did not appear to impact on how the students learned from the experiments.

6.6.2 Differences in the nature of experiments

It was only after analysing data from the two areas that it became evident (a) the students interacted differently with different sensors, and (b) the experiments were very dependant on the domains of physics and types of problems posed. A comparison of thermal physics and kinematics is presented in Table 6.2, derived from data discussed in chapters 4 and 5. Although the domains, the nature of the tasks, and students' manipulation of the sensors were different, there were no indications that the students learned their physics differently.

Table 6.2

Differences Between Kinematics and Thermal Physics Experiments

Kinematics	Thermal physics
Nature of the experiments	
Many tasks (but not all) require students to simulate a situation. The results are determined by the students' interpretation and execution of the tasks.	Tasks require setting up equipment, and the results follow relatively automatically.
More often experiments are seen as repetitive. Stories about walking, cycling and driving produce similar results.	Students enjoy the greater variety of possible experiments. Thermal physics is a particularly broad field.
"More experimental" (AR2071099).	"More interesting" (AR2071099).
Data collection	
Usually the sensor is under student control, so data is dependant on how students move the wheel.	The sensor is not usually manipulated by the student. Data is determined by temperature changes in the bench top equipment.
Lasts a few seconds.	Lasts many minutes. Students pursue productive dialogue and sometimes manipulate variables during the experiment
Kinesthetic senses are often involved.	Sight and touch senses are often involved.
Analysis	
Links to other concepts are limited by the nature of kinematics.	The experiment and display interpretation often links to many other concepts.
Subtle changes to graphs are more easily accepted as unimportant errors.	Subtle changes to graphs are remarked on and their meaning sought.
Mathematical analysis of graphs involves slopes, maxima, minima and areas.	Mathematical analysis of graphs often relates to tabular data of the properties of materials.
Pattern recognition and relationships between displacement, velocity and acceleration graphs are very important.	Comparisons are more important, either qualitatively or quantitatively.
Unique features	
Velocity and acceleration graphs are derived from initial displacement data.	Multiple activities relating to graph interpretation are carried on during experiments.

CHAPTER 7: FUTURE DIRECTIONS FOR RESEARCH AND PEDAGOGICAL PRACTICE

In the previous chapter an extensive discussion addressed the four research questions and three of the study outcomes of section 1.2. The fourth outcome remains to be discussed, namely, the researcher's recommendations for teaching practice in a constructivist MBL. This final chapter also discusses the boundaries of the present study and future directions.

7.1 DELIMITATIONS

The research was set in an Australian secondary school, with two different classes of Year 11 physics students. There were no indications that these classes were atypical of other physics classes in the country. The MBL materials, developed within the school, incorporated screen appearances and temperature sensors of a generic design. The wheel motion sensor differed physically and in pedagogical application from the widely-used sonar ranger technology (MacIsaac & Hämäläinen, 2002). However, the selection of the wheel sensor was purposeful, due to its unique ability to support concurrent experimenting by a large number of student groups within the confines of one laboratory. Additionally, the sensor is inexpensive and readily obtainable (Appendix 2).

To the extent that the context of other physics MBLs identify with these delimitations, the outcomes of this study may inform teaching practices in those MBLs.

7.2 FUTURE DIRECTIONS

This study was based on the laboratory layout and teaching strategies of the teacher's MBL. Further naturalistic studies may inform teachers about student learning and teaching practices for MBLs where the actors are changed, for example, with higher student/display ratios, teacher demonstrations, or different teaching strategies. These studies should pay attention to how changes affect network interactions, cognitive levels of student-display interactions, student discourse and graph interpretations, and the roles teachers and students adopt under these conditions.

The present MBL followed a POE approach, only one of many teaching strategies founded in constructivist learning theory. Science teachers need to know how students interact using other formats, and what consequences these may have for preparation and management of the MBL. Research reports consistently recommend that teachers structure laboratory activities. Student worksheets played an important role in the present study, but no recommendation was made as to the form these should take. Alternatives to worksheets may be explored. More needs to be known about the types and sequence of tasks, specially prepared for an MBL, that may help students scaffold learning.

While data logging and display is very fast, in general a constructivist MBL requires more time to implement. However, the actuality of life in many school environments is that the physics teacher is bound to complete a crowded curriculum. As long as this situation continues, teachers could benefit from guidance as to what types of MBL experiments have proven to benefit students at the most fundamental or effective levels. For example, kinematics and thermal physics experiments are basic to all introductory physics courses. If some aspects of physics course are best learned through an MBL experience, then in the absence of other research as to what these aspects may be, this may call for a connoisseurship approach to answering the question. Connoisseurs are teachers with a backlog of previous relevant experience, who may be consulted about their experiences in using MBLs.

Comparisons will inevitably be made between the affordances of an MBL as described in this study, and other laboratory procedures. One variation is for students to use a remote data-logger, and analyse the graphic data in the MBL some time following the experiment. Calculator-based laboratories (CBLs) have made their appearance in recent years, utilizing hand held data loggers which display data on a graphics calculator screen in real or delayed time (Brueningsen & Bower, 1995; Kreuger & Rawls, 1998; Wetzel & Varrella, 2000). Evidently each of these laboratory instruments comes with its own constraints and advantages for teaching and learning (Wetzel & Varrella, 2000). Research similar to that of the present study is needed for these laboratories.

As with all research, the present study has raised questions not pursued in this study. Can other physics teachers achieve the same outcomes as in this study, following the recommendations for teaching practice (which appear in the next section)? Are there domains of physics in which MBL methods would be counter-productive? It is conceivable that in some areas of MBL physics the required cognitive load, level of experimental expertise, or necessary background knowledge would indicate that different laboratory practices could be more fruitful. Are some skills learned in the MBL transferable to other learning areas? For example, do the skills of graph interpretation transfer to a mathematics course? These are some questions that emerge from the study and point the way to future research.

7.3 RECOMMENDATIONS FOR TEACHING PRACTICE

From the constructivist perspective of the teacher, learning necessitates more than extending students' knowledge of phenomena. It requires well-designed activities directed at "making students aware of their own ideas, asking for explanations of familiar and discrepant events, and debating alternative conceptions" (Smith, Blakeslee, & Anderson, 1993, p. 113). The MBL setting has to nurture student-student interactions and peer group discussions, allowing students to genuinely explore their world.

The research reported here set out to address a perceived need to know more about students' MBL activities with a view to eventual provision of what Driver et al. (1995, p. 11) termed "simple rules for pedagogical practice" consistent with a constructivist view of learning. In this section the assertions in chapter 6 are reconstructed into four recommendations for teaching practice. These recommendations to teachers fulfil the fourth research outcome stated in section 1.2, namely, to develop appropriate pedagogical strategies incorporating MBL activities that will likely catalyse students' construction of understanding.

1. Recognise, when preparing MBL lessons, that major strengths of MBL instruction lie (a) in its graphic display as a focal point for learning, and (b) its potential to engender a deep level approach to learning (Assertions 1, 2 and 3).

This statement indicates that beyond the explicit benefits of MBL (such as real-time data logging) lie powerful features that can be tapped to support student-student interactions and a constructivist view of learning. Previous research has usually emphasised the former benefits more than the latter.

2. Prior to the MBL lesson: (a) write worksheet tasks using a POE (or similar) format; (b) supplement these with additional resource/stimulus materials on which students can draw during the MBL; and (c) schedule time for students to practise with the hardware, software and any novel apparatus required to handle the tasks.

The reason for (a) is to structure group activities. "Principled understanding rarely arises as a result of unguided discovery" (Linn & Songer, 1991a, p. 410). The tasks should put students into situations where they draw on previous concepts, debate, discuss, and potentially create situations that bring dissatisfaction with present knowledge, or create other situations which they might not have met previously. The tasks should also be planned in a sequence to help students scaffold their understanding. Element (b) is based on Assertion 1, which effectively states that students can draw on a variety of conceptual models during student-student-display interactions, provided they are made available. Requirement (c) ensures that during the MBL lesson students will not be distracted from thinking about the experiment by attending to procedural problems. This will empower students to control their MBL experiences, and help minimise student frustration.

3. During MBL lessons, circulate from group to group, encouraging students to (a) follow the POE format and maintain complete records, and (b) use all of their resources. Adopt a questioning strategy that (c) promotes student-student-display and inter-dyad interactions, and (d) encourages students to reveal what they are thinking.

This recommendation is based on Assertions 4, 5, 6 (about student discourse and graph interpretation) and 8 (about the teacher's probing questions). Group sizes are limited preferably to two or three students. The teacher needs to know the stage each group has reached, and be familiar with relevant worksheet information on which he/she can draw, potential techniques for graph interpretation (section 6.2.1.4), and the kind of probing questions that evoke deep level responses (Table 4.1).

4. After the MBL lesson lead the class in discussion towards an accepted understanding of the experimental phenomena.

This recommendation is a response to what students stated in interviews, that they wanted to talk periodically about their experiments before moving on to new tasks.

These recommendations have a generic nature. They are not intrinsically or intentionally linked to any particular domain of physics, sensor, or MBL geography (that is the architectural layout of the laboratory and genus of hardware and software). The recommendations are sufficiently liberal as to permit a great variety of tasks and teaching strategies. They are also supportive of a teacher's epistemological commitment to constructivist theories of teaching and learning, which teachers find is challenging in itself (see section 2.4.4).

The recommendations may also sustain teachers' epistemological commitments to, and uptake of, MBL practices.

> Sparks' (1983) synthesis of research in staff development suggests that teachers are more likely to adopt a new practice when it is presented clearly with specific techniques for implementation. Further, teachers must be convinced that the

> innovation is worthwhile (from both their view and that of the students), and the result outweighs the effort. (Russell, 1991a, p. 32)

7.4 CONCLUDING STATEMENT

As stated in the opening chapter, how fitting it should be that computer technology, an offspring of physics, should be used to enhance physics instruction. For two decades now computers have increased the potential for physics laboratory activities. In more recent times laboratory practices have been changing towards a constructivist paradigm, and this has opened new avenues for pedagogical inquiry. As Tobin (1990a, as cited in Lazarowitz & Tamir, 1994) observed:

> Research is needed on how students engage, construct understandings, and negotiate meaning in cooperative groups and on how to guide teachers in establishing and maintaining environments conducive to learning. Teacher researchers are the logical inquirers in such studies. (p. 95)

These sentiments have been foundational to the present research. A major aim of this study focused on the potential of MBL methods to enhance physics instruction.

All of the stakeholders in science education – teachers, researchers, policymakers and students – are advantaged by the insights and practical suggestions that have come out of this research. Benefits will accrue to teachers for their better understanding of the types of practices that enhance student learning in an MBL. They have been provided with recommendations for materials and teaching strategies supportive of a constructivist approach in the physics laboratory. Researchers stand to benefit from the kinds of data gathering and analysis described in chapters 4 and 5, and they may take the assertions that have arisen from this study as starting points for conducting further research in this field. Policymakers have, in recent years, been calling for the application of constructivist principles of teaching and learning to science education classrooms. They have also been keen to increase computer technology in schools. Arising out of this research is a powerful rationale for the wider establishment of microcomputer-based laboratories in school physics departments. If teachers, researchers, and policymakers respond to this research in the manner suggested, physics students themselves will be the beneficiaries, in terms of more interesting and meaningful learning experiences. It was towards this end that the teacher-researcher conducted the research described herein.

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APPENDIX 1: A SUMMARY OF MBL RESEARCH

Authors	Year	Focus(es)/Conclusions
De Jong & Layman	1984	MBL construction advice on hardware, software and applications.
Jesberg & Dowden	1986	Practical advice to initiate computer interfacing; benefits were lab time saved, student enthusiasm, lab more successful, and students spent more time inferring, analysing and deducing.
Mokros & Tinker	1987	(*n*=125, 3 month study) Identified common graphing errors: graph-as-picture and slope/height confusion. A longitudinal study of heat/temperature graph interpretation skills. Even a brief MBL session resolved some common errors. MBL was effective due to: using multiple modalities, linking concrete and symbolic in real time, analysing data in an experiment context, and eliminating graphing drudgery. Time efficient.
Brasell	1987	(*n*=75, one lesson) A single lesson treatment comparison of real-time and delayed-time graphing. Real time improved understanding of displacement-time graphs, possibly due to lower short-term memory demands. Velocity-time graphs were not improved likely due to technical and experimental difficulties. Real-time graphing was a key feature for cognition and motivation.
Nachmias & Linn	1987	(*n*=249, one semester) Showed students evaluated computer-generated temperature graphs uncritically (software and hardware errors were not eliminated). Enhanced instruction in an MBL increased awareness of the sources of errors. A graph-directed rather than experiment-directed study. Authors recommended a more detailed analysis of individual students during MBL to study the dynamics of understanding
Linn, Layman & Nachmias	1987	(*n*=240, one semester) Instruction in MBL temperature graphing used experiments based on a 'cognitive sequence.' Understanding of graph features, basic templates and advanced templates all improved. MBL helped develop graphing skills and knowledge of graph templates; multiple screen graphs led to deeper understanding, however reasons for success were not clarified.
Stuessy & Rowland	1989	(*n*=75, 2 hours) Compared traditional and MBL methods of data collection and graphing of temperature. MBL enhanced development of graphing abilities. Novelty treatments can obscure conclusions.
Adams & Shrum	1990	(*n*=20, 4 hours) A comparison of MBL and traditional methods of line-graphing skills and graph interpretation of temperature graphs. Graph construction was better taught by pencil-and-paper methods. There was a medium effect size showing that skills of graph interpretation were enhanced by MBL.
Beichner	1990	(*n*=218, 2 hours) Beichner exchanged an action video for an actual experiment to isolate the aspect of MBL real-time graphing that accounted for better student achievement. Students who viewed a video animation of motion did not learn more than students who used stroboscopic photographs to draw graphs. He suggested MBL gave students control of the experiment, and (in this case) kinesthetic feedback. MBL was time efficient.

Authors	Year	Focus(es)/Conclusions
Solomon et al.	1991	Six UK classes each used a single motion sensor to imitate displacement graphs. Children's creative, shy and fun reactions were commensurate with ages. Pupils using worksheets recalled experiences better.
Rogers & Wild	1994	Three schools used timing, motion and temperature sensors. IT promoted collaboration. Posttest comparisons of IT and non-IT were inconclusive. Pupils used to IT methods spent more time discussing and investigating. Labs were more successful. Pilot study of low validity.
Nakhleh & Krajcik	1994	(*n*=14, 1 lesson) Middle school chemistry students used MBL, pH probes and indicators in acid-base titrations. Increases in understanding using concept map analysis showed MBL provided a 'higher level of information' and most effectively integrated their knowledge. Increase in making inappropriate concept links may be due to their higher involvement with the technology. Teacher mediation, pre and post lab discussions advised for lab work.
Nakhleh & Krajcik	1991	(From the same study as above). The computer display functioned as an 'auxiliary memory', not transient. Video/audiotaping was a powerful tool for examining students' thought processes.
Settlage	1995	(*n*=13, 8 weeks) Videotapes and field notes showed that third grade children expanded their graph-making and interpretive skills using light probes. MBL supported scientific inquiry by the children.
Roth, Woszcyna & Smith	1996	Year 11 physics students using a motion microworld were videotaped. The screen display facilitated discussion, and linked phenomenal and conceptual domains. Unfamiliar software and five per computer limited success.
Clark & Jackson	1998	A one year case study of year nine physics classes using technology. Data were gathered by video analysis and focus group interviews. The MBL visual display promoted motivation; students were confident of results as data were perceived as being more accurate; cognitive changes were enhanced. Some difficulties were encountered with the interface. Groups of four were too large.

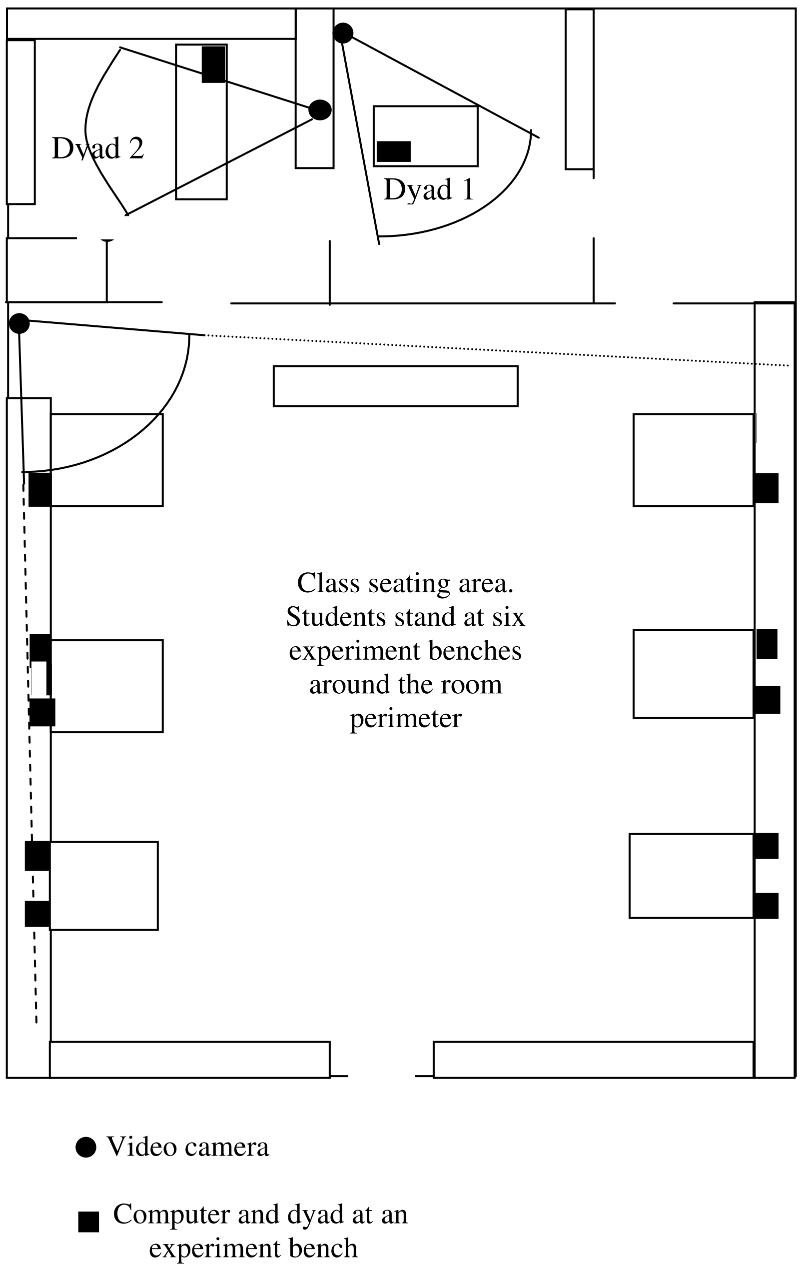
APPENDIX 2: INFORMATION ABOUT THE INTERFACE AND SOFTWARE

The interface used by students connected to the printer port of the PC. Software programs for kinematics and thermal physics used the DOS operating system, which functioned on all PC models, including early models donated to the laboratory from other school departments. The software was controlled from the keyboard so as to avoid additional crowding of the workbench with a mouse controller.

A similar interface, sensors and software are described in the file Freelab.zip, on the Physics Department page of http://www.ferngrovshs.qld.edu.au. This model connects to the games port of the PC and uses the same software.

APPENDIX 3: PHYSICS LABORATORY PLAN

Locations of computers, cameras and dyads.



APPENDIX 4: THERMAL PHYSICS: INTRODUCTION TO NEW TERMS

Heat Energy and its Measurement

Temperature: a measure of the 'hotness' of a body, using a selected scale. The scale is based on physical property that changes with temperature, such as the length of a column of liquid in a glass tube.
Celcius scale: Melting point of ice 0^0C Boiling point of water 100^0C
Kelvin scale: Melting point of ice 273^0C Boiling point of water 373^0C
Ambient temperature refers to the surrounding temperature – room temperature.

Heat (energy): the energy that flows from one body to another due to their temperature differences. Heat energy flows ONE WAY, from high temperature to low temperature. Heat energy is measured in Joules (J) (also, kilojoules, kJ, megajoules, MJ)

Thermal equilibrium is reached with two bodies at different temperatures come into thermal contact, and eventually both reach a common temperature. Because they are at the same temperature, heat flow between them ceases. It takes time for the bodies to reach thermal equilibrium. If an object has been resting on the bench *for sufficient time*, it reaches ambient temperature.

The **time constant** of a thermometer placed in thermal contact with an object, is the time taken (in seconds) for it to close 63% of the gap towards its final temperature. The smaller the bulb of a thermometer or temperature sensor, and the better the thermal contact between the thermometer and the object, the shorter the time constant.

The **heat capacity** (C) of a body is the heat energy (in joules) required to raise its temperature 1^0C.

Heat energy is transferred from point A to point B by:

Conduction: (only significant in solids). Heat flows from the hotter material to the colder material *in contact*. There is no visible movement. TO STOP conduction, separate the materials.

Convention: Currents flow in *liquids and gases*. These currents carry heat energy. Hotter fluids become less dense and are forced up by colder more dense fluids. Convection currents or thermal currents move vertically – hot fluids rising, cool fluids sinking. TO STOP convection, stop the fluid moving, or remove the fluid.

Radiation: Electromagnetic waves carry (radiate) energy away from all bodies; the hotter the body, the more radiation energy it emits. Invisible radiation is infra-red radiation; visible radiation is light.
Radiation is not a key factor in the experiments that follow.

Calorimetry experiments measure the heat energy transferred from hot to cold bodies, using a calorimeter (An insulated metal can with lid). Measurements of the materials include their masses and temperatures before and after they are added to the calorimeter.

While calorimetry involves **quantitative** study using exact measurements, the present experiments involve **qualitative** study.

APPENDIX 5: THERMAL PHYSICS: POE TASKS

In their original form the following tasks were printed one task per page, leaving spaces for students to complete prediction, observation and explanation, and occasionally answer additional questions.

Task 1
Does a thermometer or temperature sensor, initially at ambient temperature, give an *instant* reading when placed, say, in hot water?
(Hot water and a beaker are available. Also the temperature-time graph feature of the computer. Try a range of 10^0 to 80^0 and a time of 2 minutes)

Task 1.1
If the temperature sensor is place inside a narrow test tube and placed in hot water, how will this affect its operation?
Can you mention thermal contact in your discussion?
Estimate the time constant under this condition.

Task 1.2
If this sensor <u>touches</u> a hot object, such as one of the solid metal cylinders heated in hot water, how quickly will it measure temperature?

Task 1.3
If the sensor is placed *inside* a hot object how quickly will it react?
Why? How do you describe this using correct physics terms?

Task 2
Are you familiar with the statement that friction produces heat? Can you demonstrate this using: a metal rod, strip of cloth, wooden block to hold the rod, and the temperature sensor that fits into one end of the metal rod?
(Suggestions for a graph: Set the temperature range 10^0 to 50^0 and time 8 minutes. Rub the rod for only the first three minutes, but run the graph for the full 8 minutes).
What temperature-time graph do you predict?

Task 3
Saucepans are commonly made of iron, aluminium, stainless steel, or copper. Samples of these are provided as metal rods.
Problem: Which of these metals is <u>best</u> suited for use in a saucepan?
(Suggestions: Select <u>two</u> of the rods for the task, along with a beaker, water from the hot tap, and two temperature sensors. Try graph temperature ranges 10^0 to 80^0 and a time of 10 minutes).
What temperature-time graphs do you expect?

Task 4
The adult's swimming pool and the children's paddle pool are both a fine 25^0C during the daytime, but Andrew noted that at night when the ambient temperature fell quickly to 5^0C, the paddle pool dropped much more in temperature than the large swimming pool.
Rachel suggested this model: Add hot water to two identical test tubes – one with 1cm depth and the other 2 cm depth. Then let them cool in the breeze.
(Suggestion: 2 sensors; temperature range 10^0C to 80^0C; 10 minutes)
What do you predict? Why?

Tasks 5 (a) and 5 (b)
At room temperature PENTANOL is a liquid and LAURIC ACID is a solid. Apart from that, they are very similar in physical qualities. When warmed in a bath of hot water they are both clear liquids.
Predict two temperature-time graphs, for cooling about 2cm of each in identical test tubes, over 25 minutes.
Note: Place about 2 cm depth of each in identical test-tubes, and warm them to about 80^0C. Use a 250 ml beaker filled from the electric water urn in the preparation room as a water bath. Select a range of 15^0C to 85^0C and a time of 25 minutes.
Additional:
1. Estimate room temperature, and explain your reasoning.
2. Isaac Newton actually wrote a rule or statement about the rate of cooling of hot bodies. If you wrote a rule, what would it be?
When the Lauric Acid turned from liquid to solid, did the test-tube continue to loose heat energy to the atmosphere?
If so, where did the heat come from? Suggest a reason.

Task 6
James argues that heat and temperature mean basically the same thing. So long as two different-sized chunks of the same material are heated to the same temperature, they have the same heat energy in them. Fred disagrees. He claims the two, heat and temperature, are measures of two different things.
Given the following materials, how would you settle the issue?
100 g block of iron. 50 g block of iron. 50 g block of copper. 50 g aluminium. Measuring cylinder to place, say, 50 ml of water in the calorimeter. Tongs. A bath of boiling water. One temperature sensor.
(Note: If you measure the temperature of the contents of the calorimeter, continuously jiggle the calorimeter gently to 'stir' it)
What conclusions can you arrive at with the materials provided?

Task 7
Given chunks of two different materials, each of the same mass, would you expect that *different materials* contain the same heat energy if they are at the same high temperature? Use the materials provided to test your prediction.

Task 8
Do *different liquids* (quantities of the same mass) contain the same heat energy, if each is heated to the same high temperature?
Two liquids are provided, water and linseed oil. They have similar densities, so if you put 2 cm of each liquid into each of two test tubes, they will be about the same mass.
Use the same equipment and procedures as you did with the cooling curve experiments. Predict your answer to the question, in terms of two cooling curves.

Task 9
Two heating elements are provided, connected via a switch to the 12 V power supply. Each element delivers 1 Watt of power (that is, 1 Joule/second). There is some doubt that the two heating elements are identical. Both are meant to be used at the same time, heating two metal blocks at once. Do they each deliver the same heat energy per second? Design an experiment to compare them.
If they are different, work out a way of adjusting the results from one of the sensors so as to correct for this difference in future experiments.

Task 10

The question is, What is the relationship between the amount of heat energy added to a body, and its temperature rise? What factors are involved? This question calls for a number of experimental runs.

The simple answers will be qualitative. However, with careful tabulation of data, you may obtain some quantitative results, within the limitations of the experiment.

In predicting what happens before graphing each experiment, you may consider what you learned from previous experiments, and also how these results better explain previous experiments.

Materials provided: 50 g iron, 50 g copper, 50 g aluminium, 100 g iron cylinders. Insulation to hold the metal blocks. Tap water to cool the blocks after each experiment.

To summarise your conclusions, can you relate them to the formula used in the previous set of homework?

APPENDIX 6: PILOT STUDY: POE TASK SAMPLE

REMEMBER, please . . .

1. Work together and take time to discuss your views
2. Meticulously write down your Predictions, Observations and Explanations. For each experiment, complete the sequence

   Prediction: . . . .

   Observation: . . . . . .

   Explanation: . . . .

3. Sketch graphs of your predictions and observations to support your written words
4. Use correct scientific terms where possible in both speech and writing
5. Use extra sheets of A4, and number the pages.

MOTION AND DISPLACEMENT GRAPHS

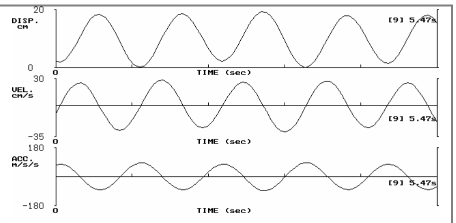
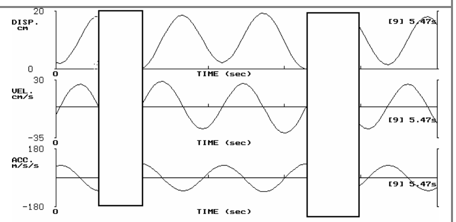
TASK 1

You roll the wheel randomly back and forth on the bench, to create an interesting displacement-time graph, which you Save. Your task now is to describe how you moved the wheel, by analysing the graph.

To do this, you probably break the graph up into small sections, and design a series of experiments to expand the sample sections. This enables you to analyse the different types of basic motion.

Finally, you return to the original graph and describe in detail the motion illustrated by the velocity-time graph.

APPENDIX 7: PILOT STUDY: VIDEOTAPE TRANSCRIPT SAMPLE

694	Don	(Don clears the screen, and recalls the second graph. He goes to the acceleration graph, which displays the graph they were expecting.)	
695	Mal	That's the one.	
696	Don	That's MUCH better. (Both look for 4 seconds.) Yeah, velocity's . . . in straight lines except where it curves like where it changes direction.	
697	Mal	(Holds a vertical sheet of paper against the screen and compares the three graphs, while Don looks on.) Zero velocity . . . acceleration.	
698	Don	Yep. (Don also holds up a sheet of paper and does the same, checking 4 vertical alignments.) Again . . and again. . . OK. (Both turn to make notes.)	
699	Don	Well that proves that one then.	
700	Mal	That proves BOTH.	
701	Don	Does it?	
702	Mal	Yep (both holding up POE sheets) zero velocity, acceleration (both turn to the screen again).	
703	Don	Velocity in one direction (pointing to screen). Ah yeah, because look if you take it say there (points to acceleration graph).	
704	Mal	If you are accelerating . . . (also points to a-t graph) if you are accelerating from a zero you've got to pass through zero (points to acceleration graph).	

APPENDIX 8: PILOT STUDY: PATTERNS OF INTERACTION

Understanding the task: The dyad discussed how to translate the task to a movement of the wheel	MONITOR ↑ TEACHER ↔ **DYAD** **→** **WHEEL** **↑** **POE TASK**
Collecting data: The dyad repeated the wheel motion until the graph appeared satisfactory	**MONITOR** **←┐** **↕** TEACHER ↔ **DYAD** **→** **WHEEL** ↑ POE TASK
Analysing and explaining: The dyad discussed the graph/s, making meaning of the data.	**MONITOR** **↕** TEACHER ↔ **DYAD** ↔ WHEEL ↑ POE TASK

As each task proceeded, the patterns and emphasis of interactions changed, as shown by the intensity of typeface and arrow. The dominant interactions involved the triad of Donald, Martin, and the monitor display.

APPENDIX 9: CONVENTIONS AND CODING OF TRANSCRIPTIONS

The following transcription conventions are adapted from those used by Roth, Woszczyna and Smith (Roth et al., 1996), with minor variations:

[. .]	Pause. Each doublet corresponds to 1 s.
(???)	Inaudible words. The number of question marks indicates the approximate number of unheard words.
(=)	Indicates a speaker overlapping speech with another.
[words]	Enclosed words facilitate the comprehension of the transcript.
(words)	Enclosed words indicate non-verbal clues and actions. If preceded by the name of a person, the following word is an interjection that does not interrupt the person speaking.
, and .	Indicate breaks in the flow of speech.
" "	Indicates the speaker is reading directly from written notes.
?	Indicates the speech is interpreted as a question.
CAPITALS	Indicates a speaker's emphasis.

Pseudonyms are used in all references to students.

Turns of speech for each dyad are numbered consecutively from 1 upwards, for as many lessons as that dyad was videotaped. For example, the turns of speech for Mel and Hank are numbered on Day 1 from 1 to 331, on Day 2 from 332 to 661, on Day 3 from 662 to 1074, and on Day 4 from 1075 to 1455.

Teacher audiotapes and journal entries are prefixed 'AT' and 'AJ' respectively, followed by the six-digit date (day-month-year).

Students' audiotaped interviews are prefixed 'AS,' followed by the number of the student interview conducted on that day, and the six-digit date.

APPENDIX 10: KINEMATICS: POE TASKS

Task 1: Constant velocity motion

Draw on the tape stuck to the bench top to show positive and negative directions (your "sign convention") for motion in a straight line.
Use the wheel to imitate constant motion that is: (a) slow forward (positive), (b) fast forward, (c) slow backward (negative), (d) fast negative, and (e) stationary.
(Try motion over 4 seconds for each case. Remember to save each graph)
What comments or conclusions can you draw from the slopes or gradients of the graphs?)

Task 2: Constant acceleration motion

Can "acceleration" be positive and negative? Perhaps "negative acceleration" is "deceleration"? What do you think?
You model acceleration and deceleration by hand control of the wheel on the bench to examine their displacement-time graphs (curves).
(Again, try 4 second runs. Save your graphs)
How do the shapes of the graphs differ from each other, and from the constant motion graphs of Task 1?

Task 3

You roll the wheel randomly back and forth on the bench, to create an interesting displacement-time graph, which you Save to disk. Your task now is to describe how you moved the wheel, *by analysing the graph*.
To do this, you probably break the graph into small sections, and compare the sections with the sample graphs from the previous Tasks.

Task 4

You can move the wheel by hand to imitate the following actions, treating each as straight-line (linear) motion.
In every case Predict the displacement graph you would expect, move the wheel to imitate the motion and record your Observation, then Explain the outcome – how did it compare to your original prediction?

(a) A person walks at steady speed down the road for four seconds, stops for four seconds, then returns back to the start in two seconds.
(b) A cricket batsman hits the ball and scores two runs. Study the motion of the batsman.
(c) A car is stationary. It then starts when the light turns green and accelerates to the speed limit. It slows when it approaches a red light, then stops.
(d) A cyclist starts from rest and cycles up a steep hill. She pauses for breath, then coasts back down the hill to her starting point.
(e) A cyclist starts from rest and cycles up a steep hill. He pauses for breath, then coasts down the other side of the hill.

Task 5

Tyson maintains that a body can have zero velocity, yet have an acceleration. Amber believes it is possible to have a velocity in one direction, and an acceleration in the opposite direction.
Are eight or both correct? Can you give examples?

With a little imagination, you can imitate all kinds of linear motion (that is motion in straight lines, either horizontally or vertically) with the wheel on the bench or on a wall: a bouncing ball, a pendulum, a weight bouncing on a spring, and . . .

You examined constant motion in Task 1, and accelerated motion in Task 2. Recall these graphs (or make them again), and predict their corresponding velocity-time graphs.

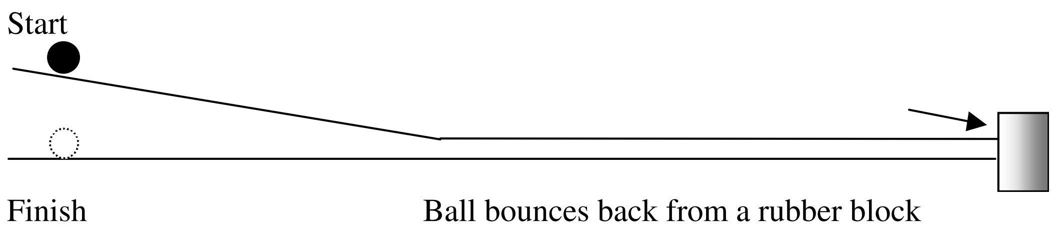
Test your predictions by selecting "VELOCITY-TIME GRAPHS" from the Main Menu. You can overlay graphs for purposes of comparison.

Task 5A

You created displacement-time graphs for the five situations described in Task 4. You can recall the $s-t$ graphs you saved, one at a time, and predict their corresponding velocity-time graphs. As a reminder, keep in mind the sign convention (the direction you chose as positive originally).
If you have time, your investigation could include identifying from the graphs (1) when the object is stationary, (2) when the object has a maximum displacement, (3) when it moves with maximum velocity, and (3) any occasions when the object returns to the starting position.

Task 6

A ball rolls down the slope as shown, bounces back at the end of the track, and returns on a horizontal track to just under the start.



Predict the displacement and velocity graphs, then imitate the motion using the wheel.

Task 7

On Day 1 you recorded displacement data for a falling weight (if not, you do this now).
Recall the data as an $s-t$ curve from the hard disk. Predict the velocity-time and the acceleration-time curves.
(Note that when we speak of a 'curve' we can also mean straight lines).

(If the acceleration curve appears 'wobbly', what could cause this? Also, what happens to the $s - t$, $v - t$, and $a - t$ graphs when the weight hit the floor?)

By entering 'D' to display data, what was the greatest speed of the weight?
What was the average acceleration downwards (by estimate)?
What was the greatest acceleration upwards?
Where was the weight at this time?

Task 8

A physicist wants to model the fall of a skydiver, and does this by dropping a magnet through a copper pipe. Due to the shortage of magnets the experiment will be demonstrated. Cotton is attached to the magnet, and as it falls through the pipe the cotton unwinds the 10-turn wheel, and the graph is drawn. A copy of the data is on the hard drive of your computer under the name MAGNET.KIN

On viewing the $s - t$ graph predict the $v - t$ and $a - t$ graphs.
Which part of the graphs models the fall of a skydiver? How?
While falling in the pipe, what is the magnet's velocity and acceleration?

When a sky diver falls (and also an ant and a rain drop) he/she reaches a 'terminal velocity.' What do you think this term means?

When falling, how would you describe the motion of say a tennis ball - (a) constant accelerated motion, or (b) constant velocity?

Task 9

Tyson maintains that a body can have zero velocity, yet have an acceleration. Amber believes it is possible to have a velocity in one direction, and an acceleration in the opposite direction.

Are eight or both correct? Can you give examples?

With a little imagination, you can imitate all kinds of linear motion (that is motion in straight lines, either horizontally or vertically) with the wheel on the bench or on a wall: a bouncing ball, a pendulum, a weight bouncing on a spring, and . . .