Modelling Physics Teachers' Pedagogical Content Knowledge through Purposeful Relationships between Semiotic Registers: *KEPLER - "Knowledge Environment for Physics Learning and Evaluation of Relationships"*

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ABSTRACT

Constructivism and considers that learning is greatly influenced by collaboration between active learners. Although learning has this social dimension, the individual learner builds a personalised version of relevant concepts. Ideas in science are not communicated solely through written and spoken language. Use is made of different types of context-sensitive, semiotic register (e.g. diagrams, graphs and equations). The science teacher expands the set of such artefacts by introducing other types pertinent to teaching and learning. The full set may be used by collaborating learners for the purpose of concept development, problem solving and knowledge construction.

It is argued that in science pedagogy such semiotic registers are not used in isolation, but are interrelated by a tutor for pedagogical purposes. The teacher may wish to highlight more semantically rich, localized areas on a semiotic and exploited for pedagogical purposes.

Although the concept of purposeful relationships may be of relevance to knowledge-based systems in general, this work considers the framework of such relationships to be a component in a teacher's pedagogical content knowledge (PCK). By investigating a representation in software of such a framework belonging to an experienced teacher, it is envisaged that pre-service teachers may gain an insight into how subject knowledge may be structured for pedagogical purposes.

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DEDICATION

This thesis is dedicated to Jim Schofield, scientist, mathematician, artist, writer and software engineer, with whom I was privileged to work for several years. There are people who are considered, or consider themselves, to be experts in particular subjects. In contrast, Jim Schofield is the only person I have met who, in addition to mastering many subjects, has then gone on to do something profound, significant and creative in all of them.

GLOSSARY

Constructionism
A consideration of how student learning may be significantly influenced through the creation of particular types of physical artefact.

Constructivism
A perspective on learning, where a student acquires their own version of concepts through integrating new knowledge into their prior knowledge.

Frame
A single, subject-oriented, computer-based artefact that represents information or activity for use in learning.

Hotspot
A focused area on a computer presented image or diagram considered by a teacher to be particularly semantically important in the learning context.

KEPLER ("Knowledge Environment for Physics Learning and Evaluation of Relationships")
Developed computer software that may be used by teachers and their students to investigate the various relationships between knowledge *frames*.

Learning Object
Instructional oriented information presented by computer to a learner. A learning object is designed to help teach an aspect of a particular taught topic and is built from one or more interrelated *frames*.

Pedagogical Content Knowledge (PCK)
That knowledge that an expert teacher has, separated from subject (e.g. physics) knowledge and generalised pedagogical knowledge, whereby concepts and skills within a taught subject are made available to non-experts.

Pedagogical Relationships
Types of purposeful relationship between concepts exploited for pedagogical purposes.

Semiotic register

Symbol based artefacts used by humans in a particular community for knowledge construction.

Chapter 1

INTRODUCTION

The educational policy of a growing number of countries includes the objective of teaching to every school pupil what might be termed basic science. The rationale behind this decision includes a belief that because of the accelerated technological changes, brought about by expanded scientific knowledge, the modern citizen cannot fully participate without some relevant scientific knowledge. However, in Britain, fewer and fewer brighter school pupils are choosing to study science subjects to a higher level, and consequently fewer of these students are choosing to read for degrees in science (Fensham, 2004). This is despite financial incentives in the form of bursaries from Her Majesty's Government and professional bodies such as the Institute of Physics (McNulty, 2004). It could be argued that, because science is required to be taught to all pupils, and not just to those perhaps brighter students who have chosen it as a subject, the academic level of the curriculum has had to be simplified. Many academics and employers have voiced their concern that the general level of conceptual knowledge, as well as basic scientific and mathematical skills, has fallen to an unacceptable level. Indeed, in order to save undergraduate physics programmes in the UK, thereby preventing those physics departments which are funded primarily through teaching from closing, the Institute of Physics has advocated a radical changes in course content including less mathematics (Institute of Physics 2001).

Unfortunately, science is perceived by many to be a difficult subject to teach and to learn. A growing number of physics teachers in schools and colleges are confronted with open boredom from their pupils. It is sad that in 2005, the International Year of Physics, "Changing perceptions of physics is a huge challenge. For many, even the word physics is an instant turn-off " (Watson, 2005). With less pressure, many more new science teachers might consider innovative pedagogical methods to overcome some of these problems. Unfortunately, it has been observed for several years that many such teachers have instead reverted to more pedestrian, conservative teaching methods (Baird, Fensham et al., 1991). To some teacher educators this indicates a lack of confidence in the novice teachers' subject knowledge. If the general level of scientific knowledge and associated skills has decreased amongst students in higher education, it may also be true of those who have chosen science teaching as their career.

When science teachers are asked what their main goal is they most often, according to Lemke (1999b), talk of getting their students to understand concepts. Many workers who have researched into the challenges in teaching a scientific discipline, in school or at undergraduate level, consider that in order for a student to be successful in problem solving, they must have acquired an appropriate conceptual framework (Mellema, 2001). However, Eick (2000) identified some serious discrepancies between student teachers' basic scientific concepts and the corresponding accepted scientific view. Worryingly, according to Kinach (2002) "... teacher educators report that the subject-matter understanding pre-service teachers bring to teacher education coursework is not the sort of conceptual understanding that they will need to develop in their future students". Indeed, Appleton and Kindt (2002) considered that in many parts of the world there has been ongoing concern about the poor state of elementary science teaching. They considered that unfamiliarity with knowledge of science and poor preparation in science content were reasons why science is perceived as a difficult teaching area.

With novice teachers this problem is further complicated since they are required to gain knowledge of science, understanding of the curriculum, pedagogical knowledge and pedagogical content knowledge (PCK). PCK is considered as a knowledge base that a teacher develops, separate from subject knowledge and general pedagogical knowledge. PCK includes how the teacher perceives the subject should be taught. As with other aspects of tacit knowledge, PCK is refined through practice. Hence, in keeping with a constructivist view of the learning mechanism, each teacher will develop his or her version of useful PCK. The question arises concerning whether a physics teacher's PCK could be modelled and whether such a model may prove at all useful in understanding the nature of one mechanism for successful teaching. Furthermore, the question arises whether such a PCK model could form the basis of designing computer-based learning tools.

Physics, as the chosen science here, could be considered as a way of objectively explaining aspects of the physical world. It shares this aim with pedagogy. Therefore, the professional physicist must have some level of PCK in addition to their general scientific knowledge, and perhaps deeper knowledge of a particular branch of physics. If human knowledge is to be considered in terms of concepts, the professional physicist, as well as the physics teacher, will have acquired scientific and pedagogical concepts. The question arises concerning the nature of these concepts, as well as the relationships between them and within them; i.e. the inter-conceptual and intra-conceptual relationships. Barwell (2000) considered that one aspect of the very idea of understanding was that of "relational understanding": an organic network of knowledge that might be adaptable in many different situations.

According to Kinach (2002), developed PCK will include knowledge of the relationships between pedagogical concepts and concepts within the taught subject. It might be that some teacher trainers would advocate that the subjects of science, e.g. physics, and pedagogy be taught in isolation, leaving the novice teacher to form personalised relationships between the various concepts. Against a background of constructivist learning theory, where the novice teacher will build their own version of knowledge, it might prove even more beneficial to some not to teach the subjects in isolation, but instead explicitly identify the various relationships. Since the relationships between the various concepts are complex and their nature varies between successful teachers, the corresponding model of the PCK is indeed personal. That does not mean that general pedagogical ideas modelled through the various relationships between scientific and pedagogical concepts will not become evident. These ideas are in keeping with Shulman's (1987) view that PCK involves "...the structures of subject matter, the principles of conceptual organization, and the principles of inquiry ...". In physics, and perhaps in other subjects, the relationships between subject concepts and pedagogical concepts may be, in fact, bidirectional. What is to be taught influences how it is taught and vice versa.

It is possibly true that the essence of what makes a good teacher is unable to be fully identified. The PCK, which an effective science teacher uses, may indeed be complex, involving many levels of those skills, which can help students, acquire their own understanding of scientific methods and concepts. It is argued in this thesis that the effective teacher's PCK skills are not necessarily independent of the subject being taught. They may be in fact related to, and underpinned by, a personalised conceptual knowledge base of interrelated pedagogical and scientific concepts. It is further argued that a science teacher's conceptual knowledge base may be modelled at least in part, and the model implemented in terms of interrelated semiotic registers. The relationships between semiotic registers or localised meaningful areas in the semiotic registers are of many types. Some of these relationships may be inherited from accepted scientific knowledge. However, there are important relationships which are exploited to aid learning. These purposeful pedagogical relationships are thought to be of importance when attempting to understand a particular, effective, physics teacher's PCK.

The thesis finally suggests that software, based on a type of learning object containing the interrelated semiotic registers, can be designed and used to help pre-service physics teachers. The software is intended to be used as an aid to discourse between these teachers. Through investigating an effective physics teacher's view of taught physics, it is envisaged that a group of pre-service teachers may gain a deeper understanding of their taught subject.

It has been argued by Lemke (1994), that perhaps only the very brightest student is able to acquire what are termed *abstract concepts*. It does appear that many science students are unable to filter out superficial differences between the problems presented to them. They may therefore be unable to extract common features, and hence fail to create their own abstracted or prototypical concepts. According to Barsalou (1999) most concepts will have perceptual components. Most concepts are strongly related to objects in the world. This relationship, which exists during the dynamic concept acquisition process, is not severed even when so-called abstract concepts have been acquired. Such ideas are important to the science teacher and any model of PCK must take into account the relationships between the concept to be acquired and what might be termed pedagogical artefacts, e.g. exemplars, real cases, typical problems etc.

Vygotsky (1978) considered that learning takes place within a social group. Even though his conception of constructivist learning was that the individual learner acquired their own version of knowledge, the process took place through a *community of learners*. Discourse between members of a community of learners requires the use of a suitable language. But of course many subjects, including physics, cannot be communicated through use of written and spoken human language alone. Physics, for example, requires the use of a rich set of languages; where the term *language is* used in a broader sense to include any semiotic[1] system. Each of the *languages* uses its own context-related symbols or signs, which may be combined according to particular syntax rules, in order to imply meaning. A physics teacher will expect students to be able to create and interpret various artefacts in which the languages are employed; e.g. diagrams, equations and graphs. Following its use by Duvall (1995), the term *semiotic register* will be used in this thesis to denote all types of artefact which may be used by a physicist as a means of communicating (e.g. circuit diagram,

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[1] Semiotics is a very broad subject, essentially concerned with the nature of signs and symbols, and how they represent meaning in a particular context. The philosophical foundation for semiotics is due primarily to the work of Charles Sander Peirce (1839-1914) and Ferdinand de Saussure (1857-1913). The unifying concepts which emerged from their work may be applied to different types of sign-based language, including natural human languages.

equations, ray diagram and graphs etc), and also those additional artefacts which belong more to the teaching and learning of physics (e.g. worked example, question and answer, etc).

Kinach (2002) when citing Driver, Asoko et al. (1994), pointed out that knowledge and understanding, including scientific understanding, are *constructed* when individuals engage socially in talk and activity about shared problems or tasks. Semiotic registers have a vital role to play in helping the group to focus their knowledge construction. For example, one semiotic register might be used to describe a problem, another used more freely to help solve the problem, and one further still used to specify the problem's solution. Because of the key role played by semiotic registers in the work of the physics teacher, modelling the teacher's PCK must include appropriate reference to them as a means of representing knowledge.

The purpose of a particular semiotic register may vary with the learning environment in which it is used. Like any method for representing knowledge, semiotic registers may be considered to have a life history. A semiotic register must be created, changed and ultimately *published* or perhaps even destroyed once it has fulfilled its purpose. In a particular learning environment a given semiotic register may be implicitly or explicitly granted its status, perhaps depending on factors such as its source (e.g. it was created by the teacher), its understandability (e.g. it portrayed appropriate meaning), its success (e.g. it led to the solution of a problem) and so on. In a learning environment where the activities are based on a more constructivist view of learning, one would expect perhaps a less formal relationship between a semiotic register and the student, since the activities may involve co-construction of knowledge using the semiotic register, with students and teacher taking part.

Chapter 2

PHYSICS TEACHERS' PEDAGOGICAL CONTENT KNOWLEDGE

Many of us can remember being taught by very gifted teachers. Unfortunately, we can also remember suffering the embarrassment of being taught badly by people who had chosen the wrong career. As Toh, Ho et al (2003) pointed out, most of us can recognise good teaching when we observe it, but it remains difficult to describe exactly what constitutes good teaching. The processes of teaching and learning (i.e. *pedagogy* if we are considering children, and perhaps *androgogy* if we are considering adults), are wonderfully complex requiring the teacher to draw upon knowledge from many different domains. Knowledge of the subject alone, such as physics, is necessary yet insufficient grounding for a subject teacher to be successful.

The term *pedagogical content knowledge* (PCK) was introduced by Shulman (1986) to describe the knowledge which an effective subject teacher has beyond knowledge of the subject which the subject specialist has. To some extent researchers differ in their definition of the term PCK. Nevertheless, there is an agreement that PCK does include an insight into those knowledge components which are related to a given topic, understanding of the common errors students make when learning the topic, and successful ways in which such errors may be overcome. PCK might be considered as a *knowledge base* separate from subject content knowledge, curricular knowledge, and general pedagogical knowledge. If pre-service teachers are taught a particular subject, such as physics, separate from aspects of teaching and learning, this might give credence to this model. In which case, for a subject teacher to be effective, he or she must be able to access knowledge from the separate knowledge bases, integrating this knowledge together in a seamless way for the sake of their students' learning.

Cochran, et al (1993) postulated that teachers evolved their PCK through revisiting the same curriculum subjects with successive groups of students. However, in certain cases this could lead to the physics teacher developing a valid, but illustratively poor and highly mathematical abstraction of particular concepts. What is fundamental is that an effective teacher must envisage the taught subject in ways that go beyond tacit, personal considerations. The successful teacher cannot simply have an intuitive, personal understanding of a particular concept. In order for their students to gain understanding of such a concept, the teacher must understand different ways of representing it (Grossman, Wilson et al., 1989).

It is a concern that in certain disciplines, most noteworthy in science, prospective teachers often demonstrate limited, explicit PCK (van Driel, Verloop et al., 1998). However, as pointed out by Davis (2003), such a problem is not limited to trainee or new teachers. Unfortunately, there are some science teachers who have taught for many years yet have not reflected on their practice. Their lack of developed PCK means that, when it comes to topics in their taught discipline, they see little difference between *telling* and *explaining*. Both identified groups of teachers may struggle to make scientific concepts understandable to their students. One reason for the lack of PCK in novice science teachers is thought to be due to their own experience as relatively passive pupils receiving a collection of facts from their teachers. Such experience is also believed to have a marked effect on the novice teacher's view and understanding of the very nature of science, often resulting in the obstruction of new ways of teaching science (Garbett, 2003).

Supporting a constructivist perspective on learning, the role played by the science teacher becomes much more complex than just being a provider of information, no matter how valid and appropriate. Even novice teachers should provide a learning environment that is rich in the opportunities for students to explore and reason about concepts (Garbett, 2003). Such an environment may be used proactively by the science teacher in what

Meade (1997) calls *teaching moments* wherein the students' conceptual understanding may be challenged, restructured and elaborated. In this environment, the successful science teacher's role becomes that of *master* with the students as *apprentices*. A pedagogical technique, now known as *scaffolding* (Davis and Linn, 2000), can be used to enhance the students' understanding beyond its current state through teacher support. New ideas and understanding can be made accessible to students through guiding them to ask meaningful and pertinent questions (Carlson, 1991), while working within, what Vygotsky (1978) termed, the *zone of proximal development*. Within this *pedagogical space* the successful science teacher may support the students, influencing them to solve problems which otherwise would be impossible.

It has been a concern for some time that the lack of depth of content knowledge has a profound impact on the science teacher's inability to acquire appropriate PCK (Carlson, 1991). Lack of knowledge of a particular science as well as a shallow understanding of the nature of science, means that the teacher may lack confidence in allowing students to explore ideas and discover meaningful concepts. Of course, as van Driel, Verloop et al (1998) and others have pointed out, the teacher must comprehend the subject they are trying to teach. However, although it is true that "to teach is first to understand", many of us have found that "to understand more deeply is first to try to teach".

Students seldom embark on studying a subject without having their own preconceived concepts. Shulman (1987) himself identified that prospective teachers come to teacher education with a set of ideas not just about the chosen subject, but also about the role of the teacher. These ideas form the basis of the teacher's subject knowledge and PCK. Whether or not subject knowledge and PCK are taught to the prospective teacher in an integrated way, it is clear that the development of each has an impact on the other (Davis, 2003). The depth of subject knowledge no doubt influences the development of the novice teacher's PCK and in turn influences how ideas and concepts are presented and information represented. However, as Toh, Ho et al (2003) point out; there are other factors which may influence the novice teacher's acquisition of PCK and their personal developing teaching style. For example, there may be societal influences such as the reticence of teachers in some cultures to allow their students to *discover* knowledge, since there may be a criticism that in some way the teacher is handing over the responsibility of their work, with a consequential loss of control.

During their career, the successful science teacher acquires a wealth of PCK. The procedural aspects of this complex knowledge are honed through pedagogical experimentation: obviously, teaching methods that do not work are adapted or rejected, whereas teaching methods that do work are strengthened, elaborated and reapplied. An expert in any field acquires tacit knowledge, which according to Sternberg and Forsythe et al (2000) is basically procedural and practically useful. Much of the tacit PCK of the successful science teacher may not be able to be made explicit. However, what might be made explicit is the successful teacher's knowledge base that contains interrelated pedagogical and subject based concepts. In addition, if such a structure can be modelled it may prove to be useful in supporting the acquisition of PCK by groups of novice teachers.

Invariably a curriculum identifies *what* subject topics are to be taught, together with the corresponding learning objectives. However, such a definition should never dictate to the experienced teacher *how* subjects are to be taught. It is only through experience that the physics teacher, or for that matter any teacher, can identify which teaching method works for a particular subject, at a particular time, for a certain group of students, in a particular place. Although the curriculum will identify major subjects, *exactly* what is taught is influenced by the PCK refined by the experienced teacher. The reverse is also true that PCK is influenced by exactly what is to be taught.

PCK developed by a successful science teacher is a complex epistemology. It clearly has interrelated procedural and declarative elements. It represents tacit knowledge that has been acquired by the teacher through experiential learning, the goals of which are measurably successful pedagogical approaches. It could be argued that the declarative aspects of the teacher's PCK will contain a personalised version of the scientific community's current view of the subject, *seen* through experience. This declarative knowledge will be incomplete, complex, non-monotonic, and uncertain; perhaps even involving so-called *misconceptions*. It will be influenced by the teacher's education, teacher training, everyday life, and practical teaching experiences.

It could be further argued that the procedural aspects of the science teacher's PCK will again contain a *personalised* view of the practical nature of the subject, including performing experiments, using particular apparatus, making measurements etc. No doubt a science teacher's PCK will also be influenced to some extent by their worldview or belief system, and their view of the nature of science, including its philosophical basis.

Several authors have concluded that unless teachers have a high motivation to teach science, they are unlikely to persist during the early teaching experiences, especially given the practical and social difficulties they have to cope with in the school and classroom. A new teacher's confidence in teaching science may have many influences including their view of themselves as science teachers, the school's policy and ethos, curriculum, resource management, and collegial support. Not unexpectedly, those teachers with clear self-perception of themselves as teachers of science, more quickly establish workable teaching practices, and are able to progress to thinking about their pupils and the learning in which they are engaging. Those teachers with less clear self-perceptions may tend to limit their early teaching practices to a few subjects and strategies that they consider safe. Extending their developing self-image as science teachers requires further specific triggering events and other support of colleagues. (Veal, Tippins et al., 1999; Smith, 2000; Loughran, Milroy et al., 2001; Spector, Burkett et al., 2001; Sperandeo-Mineo, Fazio et al., 2003).

Shulman (1986) considered that PCK must also involve knowledge of representations, including analogies, as well as strategies that were found to be useful for the teaching of a particular topic. With many experienced teachers there does appear to be a dynamic, bidirectional relationship between content knowledge, i.e. knowledge of a particular topic, and PCK. Davis and Petish (2001) found that science learners link several types of knowledge together, and this integration gives them a more robust understanding of science content. They found that prospective teachers were able to apply some scientific ideas to situations in their daily lives.

The question arises as to how the foundations of PCK can be formed by an individual prospective teacher, and whether it can be taught as a subject within teacher training courses. The focus of several educational reforms in the field of science teaching, primarily in the USA, consider a teacher's epistemological model to consist of the interplay between three knowledge bases: subject matter knowledge (e.g. physics), pedagogical knowledge and PCK. Similar ideas can be found in several authors where separate knowledge domains must interact enabling constructs underlying elements of subject knowledge in a manner that makes them accessible to students (Sperandeo-Mineo, Fazio et al., 2003). However, transforming subject-matter knowledge into PCK is not a unidirectional process (Driver, Asoko et al., 1994; Eick, 2000). Professionals in many subjects believe that it is efficacious in problem solving to begin by explaining to someone else the exact nature of the problem. This *talkback* method is clearly behind the well-worn phrase "if one wants to learn something, they should teach it". Teaching physics requires the teacher to select an appropriate level of abstraction and use the corresponding tools and symbols for the presentation of information. This process forces the teacher to look much more carefully at the subject; its concepts, assumptions, structures and methods. A successful teacher can refine their subject knowledge and PCK through careful pedagogic experimentation, making sure that all of the students gain, despite apparent failures of the chosen method. However, a novice teacher may lack a depth of knowledge in the subject and pedagogy. With this insufficient knowledge, it is difficult to start the development of personal PCK.

There has been concern for some time that student science teachers may not only lack knowledge of basic scientific concepts, but also indeed hold incorrect concepts (Beatty, 1991). Of course, the danger is that such so-called *misconceptions* might indirectly influence the acquisition of other misconceptions in the novice teachers' future students. Kinach (2002) reported that teacher educators were concerned that pre-service teachers did not bring the type of conceptual understanding to their coursework that they would need to develop in their future students. Appleton and Kindt (2002) identified that indeed in many parts of the world there was an ongoing concern about the state of at least elementary science teaching. As well as poor preparation, student teachers were unfamiliar with many aspects of the knowledge of science (Driver, Asoko et al., 1994). Bransford, Brown et al (1999) found serious discrepancies between student teachers' conceptions of some basic scientific concepts and the corresponding accepted scientific views.

Peterson and Treagust (1995) considered that it was extremely important as part of their undergraduate education for pre-service teachers to be given opportunities to start developing their pedagogical reasoning ability. Only this would enable science teaching, in their work in primary schools, to be based on sound reasoning. Ash and Levitt (2003) considered that when trainee teachers participate in formative assessment practices their professional growth can be significantly transformed. Trumper (2003), stressing the social perspective on learning in classrooms, considered that novice teachers should be introduced to a *community of knowledge* through discourse in performing various relevant tasks. This clearly identifies two important relationships, one with a Vygotskian view of constructivist learning performed by a community of learners, and the other that science education should include an understanding of how scientific knowledge is acquired. This is similar to the conclusion made by Driver, et al (1994) that students may construct knowledge and understanding, including scientific understanding, when they engage socially in talk and activity concerned with shared problems or tasks. Holt-Reynolds (2000) considered the changes in pedagogical approach influenced by constructivist learning theory. Knowledge cannot be imparted by teachers, instead it should be considered as being able to be personally created and modified, mediated by discourse. Therefore teachers must actively engage their students' participation.

Holt-Reynolds (2000) considered that a learning environment, based on a constructivist view of learning, should enable each student to actively participate in the group's construction of knowledge. In physics pedagogy, this so-called co-construction process may begin with consideration of the students' observations, ideas, interpretations and perhaps even misconceptions. The question arises regarding the role of the teacher in this learning environment, which acknowledges that the teacher also belongs to the learning group. Indeed, the student may find herself *teaching*, and the teacher must be *learning;* refining their understanding of aspects of subject knowledge, PCK and perhaps more general pedagogical knowledge. However, the status of the teacher is not the same as the student, remaining in control of the complex pedagogical process. The teacher's role as facilitator of learning is complex and, without losing sight of the various understood goals, is responsible for the new, more valid and real, relationship between students and knowledge.

In a teacher training course, just as in the classroom, teaching physics can begin by considering the students' prior knowledge. Kinach (2002) introduced a useful strategy to guide the development of PCK in novice teachers. Such a pedagogic strategy could be reused in the classroom. It begins by identifying a particular topic, through observation, explanation, experiment etc. The explanation is assessed and possibly challenged if it shows impossible or perhaps illogical inferences. A transformed explanation can result which in its turn can be challenged if it is not sustained. Clearly, the strategy depends on the communication ability of the students. Therefore, it could not be used with all groups. Just as with the concept of socially constructed subject knowledge. Cochran, et al. (1993) considered that PCK might be constructed in a similar way, renaming it as pedagogical content *knowing*.

Because of the belief in the epistemological interrelationship between subject knowledge and PCK, it has been suggested that the most logical place to study pedagogical methods is within the subject specific course (Grossman, 1990). Indeed some authors have argued that the whole concept of PCK as a separate knowledge domain is redundant. PCK is seen by them as just another aspect of the subject itself (McEwan and Bull, 1991). When considering teaching physics this latter idea is indeed a plausible possibility. Despite the popularity of attempting to model a teacher's epistemology in terms of *separate* but interacting knowledge bases, when considering science, and in particular physics, it is not easy to identify where the subject knowledge ends and PCK begins. Likewise, if the teacher spends a career teaching only physics, it is not easy to identify where PCK ends and more generalised pedagogical concepts begin.

The professional physicist who is not employed as a teacher, nevertheless uses many pedagogic methods for a variety of purposes. In discussions, brainstorming sessions, problem solving, analysis, estimations and calculations, a group of physicists will use similar semiotic artefacts as well as pedagogical methods in order to reach satisfactory conclusions. These conclusions for a professional physicist include the team members deepening their understanding as well as a particular problem being satisfactorily solved. One could argue that there is little qualitative difference between a professional physicist communicating with colleagues, and the same person teaching undergraduates students. The difference may be quantitative, for example the speed of concept acquisition, readiness to challenge assumptions, speed in making inferences and so on. Obviously, the difference between the work of a professional physicist and the physics teacher working in the school is more marked, but there are still many similarities.

It is not the intention of this work to denigrate those essential dimensions of a successful physics teacher's knowledge that are not necessarily related to the subject being taught. Peterson and Treagust (1995) emphasised that the act of teaching depends on the teacher's *personal presence*. However, they also considered the importance of what they termed *relational perceptiveness*. The didactic process is continuously being conditioned by personal, relational, intentional and contingent factors. PCK includes the knowledge of what to do and to say in particular situations in order to maximise or deepen the learning by the immediate group of students. Further still it includes the knowledge of how to challenge students, making the learning process exciting without over awing the less confident student. A teacher's knowledge, whether it is of the subject in isolation, general ideas on pedagogy, or PCK, is in a state of flux. Yet the successful physics teacher can go beyond merely coping with this complex epistemology toward using it to strengthen her worldview.

A science teacher must be a scientist. Although there are science teachers who may only use scientific methods within their classroom or laboratory, successful science pedagogy requires a healthy and consistent attitude towards the subject. Eick (2000) echoed the belief of many other researchers and teachers in stating that scientific literacy must involve a knowledge of the very processes that create scientific concepts, as well as the deepening understanding of an organising conceptual framework. Hence, PCK must include an understanding of how the theory of science is organised and how scientific inquiry takes place. He and others have pointed out their concern with the fact that student science teachers may lack the appropriate understanding of the nature of science.

When it comes to preparing today's science teacher, trainers have a very difficult task to perform. Equally difficult is the task of the novice science teacher, especially perhaps within the secondary school. One would hope that gone are the days when pupils felt that they had failed if their experimental results did not match those of the particular textbook. Perhaps even now pupils are taught a naive approach to the scientific method. Even many modern textbooks fail to identify the relationship between abstraction and experimentation. It is a fact that the physicist uses modelling techniques in order to both understand concepts and identify possible experiments which support those concepts. Many sources still consider a naive view of the world of scientific inference. Unfortunately physics students may still be taught that mathematics rules and that the real world obeys simple laws. They may also be taught that performing an experiment requires all but two measurable variables to be kept constant, then by changing one of these variables (the independent variable), the perfect law will predict the value of the other (the dependent variable).

There are many courageous teachers of physics at all levels who encourage their students to consider the nature of the physical world and how we are able to interact with it, making important objective steps on an infinitely long road towards what might be termed reality. Unfortunately there are teachers of physics who would rather stress what might be termed a super-Heisenberg view of reality which considers that we can never know objective reality.

Today's computers can process different types of data, going beyond numbers and characters. Being able to store, process and output images, movie clips, audio etc opens up exciting ways of employing the computer in the physics classroom or laboratory. This thesis considers that the computer is a useful tool to support the investigation of knowledge structures. To some extent, this has been the role of Computer Assisted Learning (CAL), but the knowledge structure considered in this thesis is the declarative aspect of a physics teacher's epistemology, including a representation of one aspect of PCK.

Many sciences make use of what might be termed semiotic registers for various purposes, including explanation and description, problem solving etc. The professional physicist will use a range of these symbol-based systems, for example graphs, circuit diagrams, charts etc. These form a subset of artefacts used when teaching physics. The physics teacher may make use of further artefacts such as worked examples, questions and answers, exemplars etc. So fundamental are these artefacts or semiotic registers in physics pedagogy that they can be considered as the basic building blocks of information at a particular level of abstraction. This thesis considers their importance in modelling subject knowledge, and potulates that understanding how a teacher purposefully interrelates them may help to understand that teacher's PCK.

Chapter 3

ABSTRACTION, MODELLING AND CONCEPT ACQUISITION WITHIN PHYSICS PEDAGOGY

When teaching almost any subject it is important to realise that many students arrive with at least some subject knowledge. With science, especially physics, students often arrive with their own understanding and explanations of phenomena that they have acquired in their everyday life. Several researchers concerned with the teaching of science (Ma, 1999) would consider that these concepts form the foundation of the student's scientific knowledge, and relating the concepts to be taught with these may be a successful instructional approach. Learning in science is seen by many more as a matter of altering a student's existing conceptions (Davis, 2003) rather than giving explanations where none existed before. As pointed out by Levitt (2001) the student must be "developmentally advanced enough" to understand the ideas being presented. The task of teaching concepts to students becomes even more difficult when the students' existing concepts are found to be invalid, called by some *misconceptions* (Gilbert and Watts, 1983; Gilbert, Boulter et al., 1998; Harlen, 2000).

The existing misconceptions may be challenged and shown to be erroneous. However, this process takes time, drawing upon the teacher's skills and ingenuity in applying appropriate subject knowledge and PCK. As pointed out by diSessa and Sherin (1998), children pay more attention to what is perceived through their senses, and this may lead them towards invalid interpretations and concepts which are difficult to lose. Science knowledge cannot be acquired solely through sensory experience (Leach and Scott, 1999) although the gifted teacher may begin with simple observations by the students. If however the student is unable to reason beyond their senses, misconceptions may remain. The fact that some science teachers, in particular novice teachers, may themselves have misconceptions, adds to the difficulty.

For the student of science, learning may take place in both formal and informal potential learning situations. We recognise that in formal learning situations, in school, college or university, learning has a social dimension. However, if we adhere to a constructivist view of learning we must recognise that students will no doubt develop their own personalised version of any concepts being taught.

Again, from the constructivist perspective, learning involves the personal acquisition and refining of appropriate concepts. A familiar model of conceptual knowledge is that of a network of nodes where the relationships between the nodes have particular strength or weakness (Davis, 2003). The nodes may be thought of as representing indivisible facts or else clusters of relevant, closely related information. Learning is concerned with new knowledge being integrated into the model that may result in new nodes, changing nodal structure, or readjusting the strengths of the various inter-nodal relationships. Such a model, albeit oversimplified, can prove useful to both teachers and students.

Davis (2003) pointed out that the quality of learning can be improved when students are aware of the level of their existing knowledge, and are able to control the learning process. A physical representation of the naive model above, possibly produced by computer software, has been found to be beneficial to both teachers and students when they consider their existing knowledge. The two-dimensional *concept map* has proved useful when encouraging novice teachers or students to observe their own learning process, i.e. encouraging them to engage in what is now termed meta-cognition. Levitt (2001) when writing on improving science students' reasoning skills advocated that meta-cognition should be incorporated into the science curriculum itself.

As with the other sciences, physics makes use of many types of physical model. Likewise, in physics pedagogy physical models have often been used as an aid to understanding. Harrison and Treagust (1998) considered that physical models had an important role in helping to build a student's personal framework of new knowledge. Their evidence indicated the value of such models in improving the student's understanding of scientific concepts, acting as a bridge between the known and unknown. In a similar way to aspects of meta-cognition being incorporated into the science syllabus, Barnea (1997) suggested that novice science teachers should be taught to understand the nature and role of models and thereby being taught a more authentic treatment of the process of science.

Sloman (1998) showed that physical models can help in explaining often difficult and complex concepts to students. However, there does appear to be significant differences between students' understanding of models and that of experts. A model has at its core an analogical relation that needs to be understood by the learner (Kozma and Russell, 1997), however Treagust and Harrison (1999) found that many students focused only on the surface features of the model. They were unable to use the model as a metaphor or analogue of the phenomenon being represented.

David Bohm (1965) had some very important things to say concerning the nature of physics which have a direct impact on the teaching and learning of physics. Physics is concerned with designing, testing and revising models. However, the models are not just those physical models identified earlier. At the heart of physics is abstraction, which in essence is a process of modelling a particular phenomenon by focusing only on certain aspects of the phenomenon using an appropriately chosen modelling *language*. However, David Bohm went further when he suggested that the process of abstraction is inextricably related to perception. His premise was that in order to make sense of anything that we perceive we are continuously abstracting.

If perception is indeed tied to abstraction, what we do in learning physics is similar to what we did in making sense of our world when we first arrived. We make sense of the world through using what David Bohm described as *internal maps.* These conceptual models are built and experientially refined through us interacting with our environment. However, since most of these maps were established early in our lives, we have forgotten the processes of map building and maintenance, and the maps are now part of our reality. This is not to deny that there is an objective world; a world of phenomena that exists independent of ourselves. We do not wish to move towards a ridiculous view of reality that is very personal. This philosophical nonsense leads to solipsism. However, we do interpret sensory input using our *own* cognitive map system.

The consequence of this philosophical view means that science is seen primarily as a way of extending our perception of the world in which we are embedded. Science then becomes a collaborative enterprise of trying to make sense of the world through finding what is invariant; that is finding the cases within a particular domain where things do **not** change and the process of stabilisation enables us to literally *re-cognise* (sic).

A physics teacher may have a whole repertoire of successful ways of doing things supported by a conceptual framework that has been built and tuned over years of teaching. Scientific concepts have been modelled using other knowledge-based structures. The most noteworthy is probably Marvin Minsky's *frames* (Minsky, 1974). These structures contain what are termed *slots*; each slot is able to hold declarative knowledge (e.g. a fact or rule) or procedural knowledge (e.g. a pointer to some software module). Frames may be related to other frames in a variety of ways including object-oriented inheritance. In that case a particular frame can represent a *class* (say, elementary particle) holding details of the *attributes* and *behaviour*. This class frame is defined as being of type *class*. Another frame (say, electron) holding details of attribute values, is defined as being of type *elementary particle*. This type of knowledge structure has been successful in developing expert systems and other knowledge-based AI software, and they are most often supported by an inference engine based on what is termed *case based reasoning*

(CBR).

The concepts, which are represented using these methods, are based on subject knowledge, not on pedagogical content knowledge. One could argue that, although they are structured according to the accepted scientific view, how they are *delivered* in some CAL program may depend upon the teacher's PCK. However, it is argued in this work that PCK, or least a declarative aspect of it, can be modelled by first considering a richer version of concepts which include the accepted scientific ideas as well as pedagogical ones.

Several researchers, most noteworthy Lemke (1994), have argued that the stated aim of many science educators, to get students to learn *abstract concepts*, is not just difficult for all but the very bright students, it is impossible. Lemke in particular argued that the cognitive process of building and refining concepts does not throw away the examples, artefacts, methods etc used when those concepts were being learnt. Concepts have context. It is further argued in his work that a rich pedagogical oriented concept (e.g. a concept to be taught according to some curriculum) cannot be mapped easily on to simple knowledge structures. However, certain aspects of this concept can be represented in terms of basic pedagogical structures (semiotic registers), together with the purposeful relationships between them. This knowledge structure and its implementation as a computer program are at the heart of this work.

Designing, testing, refining and elaborating models is central to science. Indeed, it could be argued that it is at the heart of all learning. The physics teacher must be in control of an environment, which enables all participants in the learning process to "... construe general and special human experience into the categories and relations that characterize [a] unique disciplinary perspective" (Lemke, 1994). Although the term abstraction is more familiar to the software engineer, the term exemplifies the modelling mechanism used by the physicist. An understanding of the term is vital to the physics teacher and ought to be introduced to physics students as a essential part of a scientific process as in part *b* below:

a. observing phenomena,
b. designing an appropriate model to *explain* a phenomenon,
c. predicting phenomenological behaviour from the model,
d. designing an appropriate experiment to test the model's validity,
e. observing new phenomena,
f. refining the model, and so on.

How are we to understand what might be taking place when abstraction is used by the physics teacher? Perhaps we should begin by considering a possible model which could be introduced to novice physics teachers. Understanding a possible explanation of the abstraction process obviously requires us to use abstraction, and we might use models familiar to most novice physics teachers; e.g. the structure of the brain as interconnecting neurons (using a *connectionist* view point), or perhaps their knowledge of the nature of concepts (using a *symbolic* viewpoint).

Signals received from one of our five senses are registered by the brain and matched against previously learnt classes of signal. The particular signal type identified may be part of the signature of a whole set of higher order concepts. That is, the recognized signal may be an attribute of a whole set of different concepts. However, since the observation of the signal takes place in a particular context, and by a human with a world view or belief system, the search space of relevant concepts can be reduced, or perhaps the concepts may be weighted by relevance.

Matching against a particular concept means the consideration by the human of a new *case* or *instance* of this concept. Using software engineering terms we would possibly consider that a new *object* belonging to the identified *class* has been created. An inference mechanism or prediction system may then be triggered. Such a system may predict other expected signals which should exist corresponding to other properties of the concept. Attention can be drawn to other associated signals in order to gather further evidence. The concept may orientate the observational system to look for certain signals which are characteristic of the concept, whilst ignoring some signals which are not. Thereby the concept partly controls what is observed acting as a bias filter for input data. If successful the concept reinforces the perception.

The physics teacher begins with a personalized set of concepts. Hopefully these concepts will encapsulate the accepted ideas within the subject called physics. However, since the concepts are acquired by the unique experience of *that* teacher there may clearly be subtle differences in inter-conceptual and intra-conceptual relationships when compared with those of another teacher. The aim of the physics course is to enable a student to acquire valid and appropriate concepts which, for example, can be successfully used in problem solving. There is no direct link between the teacher's concepts and student concepts. The teacher must use a whole spectrum of methods to enable the student to acquire concepts and the student will acquire their own versions. The teacher will use abstraction in order to orientate the perception of observable phenomena for the student. In essence the teacher wishes to formalize how the student *sees* some phenomenon.

To help this abstraction process physics makes use of a wealth of different physical models which focus or channel the perception through the use of symbols. A diagram drawn on paper for example may be a semiotic representation of a phenomenon, together with perhaps some aspects of the concepts behind the phenomenon. Any explanation of a phenomenon requires the choice of the *level* of abstraction. This term is used to describe the meta model of abstractions as hierarchical, somewhat reminiscent of the notion of classes in an object orientation paradigm, with detail decreasing with height. Perhaps, without consciously knowing why, the physics teacher chooses a level of abstraction in which to couch an explanation of the phenomenon to students. It is clear from the readiness of physics teachers to select appropriate ways to explain a concept behind a phenomenon, that the explanations and conceptual view of this type of phenomenon form part of the overall pedagogical structure. Agreeing with Lemke (1999b), it appears that perhaps even experienced teachers have not acquired *abstract* concepts. Instead, they have acquired context related, complex concepts which incorporate explanations, semiotic representations and exemplars etc. Such a cognitive structure may include a set of necessary and sufficient rules, or a set of defining prototypical attributes, which may be used to identify whether or not the concept relates to a new case or problem. The idea of the existence of an abstract concept may be understood in terms of such rules or attributes.

Within a constructivist learning environment it is important for pre-service physics teachers to understand that the acquisition of concepts by themselves, or their future students, appears to be a process of refinement as well as incorporation. Newly acquired concepts may have a complex inner structure with relationships between semiotic attributes and memories. The process of incorporating a concept into the student's epistemological structure may require abstractive processing which attempts to find sufficient relationships between the attributes and existing concepts. Successful incorporation may require refinement of existing and new concepts, and should result in the strengthening of similarity relationships.

How we individually view the world will depend upon the concepts we use. The physics teacher can only attempt to indirectly influence the acquisition and elaboration of a student's concepts. There is no direct link between a teacher's concept and a student's concept. Therefore the responsibility of the teacher is to use a rich variety of situations which may promote conceptual change. It is interesting to consider that the novice physics teacher's concepts will also change during these pedagogic processes.

According to Clarke et al (2003), abstraction is a process which maps a given model into a less complex model which retains "the behaviour of interest". The word *abstract* can be used to represent a modelling process or the end product of that process, namely the target model. It could be argued that, if the practice of science is concerned with describing, understanding and predicting aspects of the physical universe, then abstraction is the *tool* we use, and an abstraction is a *representation* (literally re-presentation) or model of some aspect of that same physical universe.

The dictionary definition of an abstraction usually stresses that it is a concept or idea which is not limited to a particular instance. The term therefore has many synonyms depending on the current *universe of discourse* under scrutiny. In psychology or even perhaps pedagogy we could use the term *concept*. In categorisation theory, we might use the term category, or perhaps when modelling a system using an object oriented (OO) approach, we might use the term *class*. The dictionary definition of the abstraction process often stresses the act of leaving out of consideration certain properties of *particular* cases or objects in order to describe the *set* of them, and thereby identifying the similarity between items belonging to the set.

A discussion of the physics teacher's use of modelling and abstraction would be incomplete without considering the role of the modeller. Indeed, the very first step in this modelling process is the development of a conceptual model, a way of thinking about the physical system under consideration. This will require a consideration of how to represent it (Edgington, 1997). The person using one of the objects to represent, in some way, the other object, is using a purposeful conceptual model. This conceptual model must have representations of the context, both objects, the properties of the objects under consideration, the mapping of the properties, and hence the mapping between the objects.

The idea of choosing one object to represent another, that is the process of abstraction or modelling, is the fundamental mechanism used in physics. Graphs, a written equation, a circuit diagram, are all types of physical model used in physics. When teaching physics, if the teacher tries to explain something using perhaps gestures, or draws a diagram on a blackboard, or gets a group of students to play at being electrons, she is also involved in a process of abstraction, i.e. she is also modelling.

We expect science students to use a wide variety of models. To some interested in the teaching of science, models can act as bridges between the known and the unknown (Hardwick, 1995), hence becoming an integral part of the building of the student's personal framework of new knowledge. Others (Harrison and Treagust, 1998) consider models as a way of improving the understanding of scientific concepts, acting, as considered by Gilbert and Boulter (1995), as an intermediary between the "abstractions of theory and the concrete actions of experiment". Many agree that science students, in particular physics students, should know precisely what a model is (Hestenes, 1992), and that novice science teachers should be taught to use models in a more scientific way (Gilbert, 1997).

They may be asked to design and build a model, interpret the meaning and hence extract information from a model, even convert one type of model into another. Physics is no different from many other subject when considering the use of models and modelling techniques. When considering the problem solving ability of a physicist, Mayer (1992) suggested that what is required is a *cognitive toolkit* containing mathematical, diagrammatic, rhetorical tools as well as a whole spectrum of strategies. The physics teacher also needs such a toolkit, but also a complex, adaptable and relational conceptual structure of physics and pedagogy. But abstraction is a more fundamental aspect of physics still. The central theme of physics, which needs to be taught to physics students and prospective teachers, is that we do not merely report observations, we construct concepts and theories (Alur, Henzinger et al., 2000). Abstraction is the means of understanding not just of describing.

Some physics courses may be more practically based, few may include a study of the work of famous physicists, and others may be more mathematically intensive. Most require the student to solve problems, and in order to solve such problems most educational researchers consider that the student must first acquire an appropriate conceptual framework (Mellema, 2001). Despite being taught in the same way, performing the same experiments, reading the same textbooks, taking part in the same discussions, each student's conceptual framework is personal, or at least personalised. Some novice teachers may be surprised if not concerned about this. "Surely", they might argue, "physics has laws". "Students cannot be allowed to have their own versions of these laws, can they?".

This should not be a problem, rather it should be a pedagogical opportunity. It may be that in their training course the novice teachers' views of the nature of science has to be enhanced. The growth of science, that is, more exactly, the growth of abstractions used to understand (perceive and predict) the world, is dynamic. At any one time the world's community of physicists will agree on certain models, but disagree on others. It is only through repeated experimentation and abstraction-based explanation that agreement will be reached, and some principle, which may be adhered to by the scientific community, emerge.

When we use abstraction to the level that all qualitative description has been removed, we are left with, often trite, quantitative statements. For example, a school student may use the statement "the angle of incidence equals the angle of reflection". This can be quite a useful statement. But when understanding abstraction, new teachers of physics should realise that it is based on certain major assumptions. When considering this so called *law of reflection* we do not have a beam of light; the beam has been replaced by an infinitesimally thin *ray*.

We do not have a real mirror; we have a perfectly reflecting surface. The statement is true as an abstraction. If we teach physics as a set of rules or laws, without teaching how these have been abstracted, the student will end disappointed with any practical work, since it is very difficult, especially in a *school* laboratory, to get, for example, friction or thermodynamics experiments to reproduce what a textbook might state

Many teachers understand that it is only the very bright student that is able to acquire what might be termed an *abstract* concept; that is knowledge that can be applied in many different contexts in, for example, problem solving exercises. Lemke (1994) argued that even the brightest students do not acquire abstract concepts. Instead concepts that were learnt could not be divorced from contextual knowledge. Hence, if we are to teach physics effectively to all students, emphasis should be on the pedagogical process whereby abstracted models may begin to emerge as generalisations from rich examples of contextual knowledge. We cannot teach concepts verbally, they are acquired through activity (Piaget, 1980). If we wish to influence the validity and depth of the concepts which our physics students acquire, we can make use of a wealth of appropriate learning activities. These activities can be based on experiments, discussions, role play etc. Each activity along with the contextual knowledge involved will have important semiotic elements. This thesis considers that in physics there are important types of semiotic register which have a vital role to play in abstraction and model building. Furthermore, such artefacts are necessary for the acquisition of concepts and are commonly seen being used in physics lectures, in all physics textbooks, and in material published on the World Wide Web.

Abstraction is a context sensitive way of *seeing* some aspect of reality. Abstraction allows certain properties of objects to be ignored, whilst other properties are emphasised. Hence different objects can be categorised as related in some way because they share similar properties. Abstraction continues by selecting a means of representing (as literally *re-presenting*) the filtered, *seen* object system using appropriate language. *Language* must be interpreted here in its broadest sense; with its symbols, obeying rules, encapsulating meaning.

Instead of the fruitless attempt to impose physics ideas on students, more time should be spent in experimentation and abstraction techniques. Students should be encouraged to discuss more and draw how they see particular physics problems. Physics is a subject with practical and modelling aspects, yet too little time is spent in teaching students how to accurately observe and then describe what they observe. Kuhn (1974) stated that although explanation was the very nature of science itself, there was disagreement on the part of teacher trainers regarding what this meant in teaching science. This still appears to be the case today.

If physics students are to acquire valid scientific concepts, perhaps through the use of models and the process of abstraction, it is important to realise that this is not done in an environment free from bias. Physics students in schools and universities expand and enhance their knowledge against a background of unwritten assumptions and influences. Kuhn (1962) considered that what he called a *paradigm*, the shared intellectual framework, attracted and guided the work of scientists who were adherents of a particular domain. Such an epistemological influence does not rapidly change, although at any given time there are phenomena, the understanding of which it does not address. One of the ways in which it influences scientists, and in turn science teachers, is through accepted models.

Unfortunately there are other influences on the students' use of models and abstraction in physics. Physics is not taught to the student against the background of a fundamental search for truth. Instead it is taught within an *educational* system which has its own orientation and bias. The student's acquisition of concepts may well be influenced by the contextual stress on uniformity, discipline, and assessment etc. It may be that only the brighter physics student is able to filter out these academic organisational influences.

Chapter 4

THE IMPORTANCE OF SEMIOTIC REGISTERS IN PHYSICS

Scientists, are unable to communicate their observations and ideas through relying solely on verbal language. Lemke (1998), using a modern term, described physics as being a *multimedia* genre. It is not surprising therefore that studying physics requires extensive use of different types of semiotic systems. Duval (2001) considered that members of a professional community, such as physicists, make use of a variety of cognitive tools such as written language, mathematical notation, various types of diagrams and computer software when engaged in what Lemke (1994) termed *social semiotics*. Such cognitive tools are used to create what has come to be termed *semiotic registers* for use in developing and communicating ideas as well as in solving problems.

In a not dissimilar way the science teacher may take part in the social activity, of what might be termed *making meaning*, jointly with their students, documenting the co-constructed knowledge through the use of semiotic registers. Shank (1995) considered that through discourse between members of what Vygotsky (1987) called a *community of learners,* various cultural resources were employed in helping to model the particular types of experience of the group. The semiotic registers, which are the physical end product of this modelling process, are at the same time physical artefacts in the world of the physicist or physics teacher, as well as semiotic artefacts which represent how the group sees the various categories and relations which make up the particular discipline.

There are types of semiotic register which are used by both the professional scientist and the science teacher, for example graphs, charts, diagrams, and equations. There are of course other semiotic registers which are used by the science teacher because of their pedagogical role which are not necessarily used by the professional scientist; among these are questions, worked examples and what Kuhn (1974) called *exemplars*; a typical problem and its solution which stands as a standard example, exemplifying a particular paradigm.

Semiotic registers are essentially symbolic representations of knowledge within a particular context, enabling, as Duval (2001) pointed out, channelling, or we might argue constricting, the participant's perception of the particular environment, and enabling, or perhaps limiting, the operational interaction with that environment. A semiotic register is not however *intrinsically* meaningful. For the recipient to interpret the semiotic register's meaning in a similar way to the designer, both parties must perform authentic analytical processes which identify relevant relationships between the symbols, and between the symbols and the information being represented. However, the ultimate significance of a sign is rooted in the consequences of interpreted habits and orientations it generates in the social group (Chandler, 1995). Clearly there must also be an agreement between both parties on the context in which the semiotic register is used for valid indirect transfer of meaning. It is interesting to note that Noth (1998), citing earlier ideas by Uexküll (1940), suggested that in mathematics the use of semiotic registers was essential for the very development of mathematical thought. It could be argued that, were it not for semiotic registers, physics might be merely concerned with the taxonomy of qualitative observations.

When the use of cognitive tools is shared by a group of students, especially in a constructivist learning environment, the collaborating learners may be empowered to co-construct knowledge. This is particularly true when the cognitive tools are computer programs which have been shown to enable mindful and challenging learning when compared with other less student-centred or task-oriented instructional technologies. Supported by teachers, cognitive tools can prove a major pedagogic benefit when applied to tasks or problems which have been defined by the learners themselves.

In the sciences, meaning is constructed in and through discourse, and as Lemke (1994) pointed out such discourse requires the use of various means of communication in addition to talking and writing. In physics, as in many other subjects, diagrams are used for a variety of purposes and may be given different levels of status. Diagrams are used as part of the process of problem solving; often being a means to the solution as well as a statement of the solution. It is not unusual to find groups of physicists sharing their ideas through the same diagram and readily transferring information from one mode of representation to another. Indeed, shared diagrams take on an important status in the work of a physicist, and different modes of representation naturally play their part in the development of concepts.

It is unfortunate that diagrams as a shared dynamic tool are not readily accepted by all students and their teachers. Anecdotally there are several possible reasons why diagrams appear to have a different status when used pedagogically. Diagrams drawn by the teacher may be seen as more important and therefore more valid than those drawn by a student. Drawing a neat diagram may be considered as important as drawing a meaningful one. Some students may be embarrassed in drawing a diagram which other students may see. Although diagrams may be seen as important semiotic registers for the transfer of information and for problem solving, they still appear not to be promoted enough as vital, dynamic, valid, pedagogical tools for use by all students whether working on their own or in collaboration with other students.

Professional physicists, teachers and students are required to be able to create and interpret the various types of diagram used in physics. However it may be that too little time is spent in teaching the use of such vital semiotic registers. The various types of diagram are shown to be useful when communicating information, as aids to problem-solving, and also in discovery learning. Clearly there should be a relationship between the diagram's purpose and how it is interpreted in the particular context in which it is used. In many subjects including the sciences, mathematics and technology, diagrams play a supporting role in reasoning. There are claims that by integrating the use of various ways of representing information, e.g. text and diagrams, memory and perhaps even higher cognitive skills are aided (see for example: Sweller and Chandler, 1994). The so-called *cognitive load theory* considers that such a result is due to significant processing taking place within both hemispheres of the brain.

Professionals in many subjects, including physics, often take the use of diagrams for granted. However, many students do find diagrams difficult to interpret. There are clearly several possible reasons why this may be the case. A student may be introduced to a new type of diagram at the same time as using the diagram to aid in the understanding of a particular subject. For example, a student may be presented with apparatus making up a simple DC circuit, shown the equation representing Ohm's law, and given a circuit diagram. The overall pedagogical objective is perhaps achieved through the student considering how the equation and diagram are abstractions of the circuit. However, in the case of the diagram, if the student is not able to make the appropriate mappings between the various symbols and the corresponding apparatus, the method to achieve the objective is flawed.

The student is required to understand the perhaps idiosyncratic nature of the diagram whilst using it to reinforce understanding of various concepts. The meaning of particular symbols in a diagram will often depend upon the diagram's purpose in the context in which the diagram is used. Almost identical symbols even placed in different parts of the same diagram may represent different things. Some of the properties of particular symbols are to be interpreted as important, and carry meaning, whilst other properties may be ignored. Meeting even the simplest electrical circuit diagram for the first time can confuse many students. A diagram which represents how simple electrical apparatus is wired together will contain symbols for each piece of apparatus which have been accepted by the physics community. A simple cell is represented by two parallel lines of unequal length and thickness; these are a stylised representation of the cell's electrodes. Even though a particular elaborate symbol is a composite structure, as in the case of the cell, the physics teacher requires the student to use the complete symbol as an undifferentiated whole. But, for example, if the student fails to grasp this subtlety, he or she may erroneously infer that there is a break in the circuit, since the two parallel lines representing the electrodes are separated by a small space. On the other hand the student may be unsure whether the lengths of the lines representing the cell's electrodes have any meaning.

In a learning environment there are clearly many factors which may influence whether a student is able to consistently associate a symbol with its intended referent. It is unclear whether knowing why a particular symbol has become associated with its referent helps students remember the symbol. As with mathematics, some students have the ability to associate even an arbitrarily chosen symbol with an object. Other students are only able to associate symbols if there is a recognisable topological relationship, as in the case of a capacitor being represented by two parallel lines representing an end view of the plates. Unfortunately, because of its international origin, the set of symbols commonly accepted by the physics community contain various types of explanatory metaphor for symbol-object association. It may also be the case that alternative symbols are available, which may confuse the student even further. For example, in a DC circuit a resistor may be represented by a small rectangle or alternatively a zigzag line. The rectangle symbol may owe its origin to its similarity to the side view of a common type of resistor. The zigzag line relies on a more complex metaphor. The symbol may represent a zigzag pipe through which a liquid flows. We would expect that the shape causes turbulence in the flow of the liquid, hence acting as a resistance to that flow.

A diagram is not a uniform, two-dimensional field, where each part is equally important. Since a diagram is two-dimensional, unlike text which is in essence a one-dimensional stream of codes, we cannot predict the order in which the various parts of the diagram are observed by the student. Indeed, in different contexts there will be certain localised areas in a diagram which have more semantic importance than others. For want of a better word these localised areas are here called *hotspots*. Encouraging the student to identify the particular hotspots, how they are interrelated, how they relate to the whole diagram, and of course their meaning, may lead to interpreting the role of the diagram correctly. Clearly, as reiterated by Blackwell (1998), the user of any diagram must interpret it according to the intention with which it was constructed.

Diagrams are useful tools of thought and communication. There is however no clear definition of what is meant by the term diagram. Lemke (1999a) introduced at least a working definition considering that something was a diagram if it contained distinct localised parts, or nodes, and lines, possibly together with the use of labels and colour. In a particular context, meaning may then be applied to the various combinations of these elements; for example, nodes linked by lines, overlapping nodes, combinations of lines, labels, items of the same colour and so on. With the aim of possibly interpreting diagrams by computer, AI research has enabled the development of more formalised visual languages. Research has identified possible lexical elements and syntactic constraints which, when used in a particular context, might enable a diagram to be processed by a computer system. However, if physics teachers are to be successful in getting their students to satisfactorily use diagrams there are other psychological aspects of perception to be considered.

Developing a thorough understanding of the use of diagrams in the teaching of physics is surely one desirable aim of PCK. There is still controversy over the status of diagrams in teaching and learning, but they are a vital cognitive resource for the novice physics teacher and the physics student. Understanding something of the process of perception of diagrams, including when they are presented to the student along with other semiotic forms, should prove of benefit to the novice physics teacher. It is known that associating an image or a diagram when presenting verbal information will improve recall by the student (Paivio, 1983). There are several identifiable stages concerned with the perception of diagrams used for pedagogical purposes. The teacher may wish initially that the student recognises the diagram as a whole, in order to initially classify it. Then perception of the diagram's parts can begin. According to several authors, (for example: Lemke, 1998), the student may group various related symbols into perceived wholes. If a diagram is presented alongside other information, e.g. a textual description, the student may be able to aggregate more of the symbols into a meaningful whole. There are other factors which may influence this aggregation of symbols including *proximity* and *similarity*. If the context is known by the student, the perception of the diagram will be influenced by the student's personal context-associated concept. Once the context is accepted, the student may possibly use abductive reasoning in order to test the validity of the diagram and, if the diagram is found to indeed be valid in the given context, the perception may lead to additional evidence which may reinforce the student's understanding of the concept.

Some authors, including (Lemke, 1998), have argued that the process of perception does not necessarily lead, through further abstraction, towards context-free or abstract concepts. Whether such a process exists or not, that is whether abstract concepts are developed or not, the learner may include the diagrams and other semiotic registers as part of the developed concept. If this is the case, intra-concept relationships involving semiotic registers are integral part of what should be taught in the physics course, and such ideas should be discussed with novice physics teachers when developing their PCK.

Blackwell and Englehart (1998) pointed out that during the social semiotic practice of *meaning-making*, an object, initially considered as a symbolic unit, may be construed as being composed of smaller subunits. If this is the case then these subunits may be considered as building blocks and combined in different ways to make new meanings possible. The culture is then free to evolve new restrictions on these combinations, endowing them with yet another dimension of meaning. It is quite sad that science students are generally not encouraged to be more creatively free in investigating how new combinations of identified symbols might represent things in the real-world. This pedagogical activity may be associated with constructionist learning and the element of *play* as suggested by Papert (1991). Obviously such activity must be supported by a teacher with a depth of content knowledge and PCK. Unfortunately, it can be the case that diagrammatic *form* is judged by the teacher as more important than *content.* Instead of using them as a means to a learning end, diagrams are considered as ends in themselves. Emphasis is placed on the students' overly neat drawing skills. The result of this seems to be that many students are reticent to create diagrams unless they can be sure that the resulting diagram is perfectly correct.

The physics teacher who follows some of the ideas introduced through social semiotics, especially in a constructivist learning environment, must face a series of apparent paradoxes. Scientific knowledge is something that is developed by a community through experimentation and discourse. The resulting knowledge is published and shared, yet each individual has their own version of a particular concept which has been acquired through their own personal epistemological development. A scientific concept is *associated with,* some might say *totally dependent on,* the various semiotic registers designed to represent particular facets of meaning (Lemke, 1998). As far as the physics teacher is concerned, the pedagogical process ends with cognitive changes in the students. Even though these are changes in the unseen students' brains, the physics teacher can only infer and assess these changes through observation and interaction with the students. Apart from watching how students use particular apparatus in a physics lab, the evidence for the assessment of the students' cognitive changes will be based on further use of semiotic registers. The novice physics teacher may ultimately realise that a scientific concept itself may be used as a single undifferentiated place holder, or notional sign, within the semantics of discourse, and is manifested in and through the various activities of the scientist, including those social semiotic activities which attempt to make the concept more real to others.

Diagrams are particularly important cognitive artefacts, according to Etkina and van Heuvelen (2001), lying in a continuum between two other types of artefact, namely text and pictures. In physics, as in the other sciences, they are found to be a vital way for communicating information, but also have important roles to play as aids in problem-solving and knowledge discovery. Etkina (2002) found that it was particularly beneficial for learning, to help students construct their own versions of standard diagrams representing physics ideas before they were introduced to a mathematical representation. However, Blackwell and Englehart (1998) question whether or not the use of diagrams as an aid to learning concepts may inhibit the development of abstract concepts. Of course, if the ideas of Lemke and others are valid, attempting to teach abstract concepts is not an appropriate direction to take science students. Instead the students' personalized concepts are developed and enriched through use of all appropriate representations and models. If the ideas of Bohm (1965) are valid, perception requires the acquisition of concepts and this dynamic process requires continuous abstraction. Visualisation may indeed be beneficial in reinforcing particular levels of abstraction.

The physics teacher should not underestimate the pedagogical importance of diagrams and other visualisation techniques. Ausubel (1968) found that historical accounts of scientific discovery and invention often mentioned the cognitive role played by visualisation techniques. He inferred that visualisation is indeed essential to problem-solving, arguing that the visual forms of representation can offer advantages over linguistic methods by showing spatial interrelationships. It is noteworthy that diagrams have been found to be essential tools for the professional physicist when dealing with the relatively modern concepts within nuclear physics and quantum mechanics. Here the symbols and spatial nature of the diagram may not represent the macro phenomena observed by the physicist. The diagram must take on more of a metaphorical role, as discussed by Blackwell (1998), rather than a simpler analogical role as discussed by Beveridge and Parkins (1987). It is difficult to answer students' macro oriented questions such as "what does an electron look like?" The professional physicist would probably select a mathematical equation as the abstraction to explain micro-phenomena. Unfortunately, the physics teacher cannot begin explaining using such a high level of abstraction. Instead, a diagram would be perhaps chosen, although even this level of abstraction is not without semiotic problems. In the case of atomic physics for example, diagrams may be used which rely on mapping non-spatial parameters, in the represented phenomena, to spatial parameters, in the diagram.

Acquisition of enriched conceptual understanding may be fostered in physics student by encouraging them to use multiple ways of representation and modelling. Being able to convert one representation into another, as well as using various tools, including software, may promote higher order cognition. It has been acknowledged by those psychologists concerned with a theory of cognitive load that more effective processing capacity is available if learners work in multiple modes (Tuovinen, 1999; Oviatt, Coulston et al., 2004). This is thought to be due to the different modes of thinking being performed by the different hemispheres of the brain; the right hemisphere being home to the visual, spatial, analogical and parallel processing capacities, while the left hemisphere is used for verbal, linear, sequential and logical processing. Sharing the cognitive load through use of multimedia representation has been exploited by many researchers concerned with educational technology. Given adequate time, as well as access to appropriate technology, groups of physics students or novice teachers may be encouraged to construct multimodal representations of their knowledge. Through incorporating various visualisation techniques the learners can explore different ways of representing concepts as well as exploring the richness and complexity of relationships within and between those concepts.

In teaching any subject it has been found to be advantageous to help students to understand how they learn. Promoting this so-called meta-cognition enables students to take more control of the learning process, observing themselves and enriching the pedagogical experience. One of the meta-cognitive strategies found to be useful is that of *self-explaining,* where the student is encouraged to explain their understanding of material presented to them. Ainsworth and Loizou (2003) found that students presented with information in diagram form produced more self-explanations than those given textual information. The self-explanations also tended to be richer in the former group. However, how students use diagrams is not without its problems. There are major differences between how experts and novices perceive and use visual representations including diagrams (Tabachneck, Leonardo et al., 1995; Hogan, Rabinowitz et al., 2004). An expert will use a whole repertoire of different diagrams and other representations, each of which may facilitate a different range of tasks. The expert is able to move cognitively between the different representations (Kook and Novak Jr., 1991). Students need to be taught the nature and purpose of diagrams so that they may make informed choices between representations when solving problems.

The relative unpopularity of studying physics beyond the compulsory part of the national curriculum means that far too few students have the opportunity to experience the evolution of their understanding of the physical world. The mathematical content of many physics courses within higher education has had to be significantly reduced with the possible consequence that the student must rely more on other means of representing fundamental concepts. The role played by multiple ways of representing ideas in physics has necessarily had to be strengthened. In a multimedia age the novice physics teacher should perhaps not reject any potentially useful way of explaining fundamental concepts using the tools of visualization. However, given the possible validity of the ideas of Papert (1991) on constructivist learning, physics students should perhaps be encouraged not only to use standard types of diagram, but also to invent and build new types.

Chapter 5

MODELLING PHYSICS KNOWLEDGE FOR TEACHING

It is always interesting to debate with novice physics teachers whether they should be teaching *physics* or *Phyllis*; that is whether their focus should be more towards the subject or the student. Our aim of course is to teach *physics* to *Phyllis*; but what does that really mean? The syllabus of any physics course or, in the case of the current national curriculum, any science course with some physics content, may identify the learning outcomes, but only broadly suggest appropriate teaching and learning methods. If we consider a constructivist learning environment to be valid we consider that each student will learn their own version of the taught subjects. Therefore the teacher's role may have to adapt from one of imparting knowledge, to one of fostering co-construction of knowledge. Because the knowledge we wish the student to acquire is not a matter of opinion, the teacher must still be the senior partner in this endeavour. Always with access to limited resources, the successful physics teacher must design an environment which will give all students ample opportunities to acquire valid concepts and skills, through use of a variety of potential learning mechanisms including discourse, experimentation etc. We wish each student to gain a coherent understanding of the subject, rather than a patchy and compartmentalised one, therefore the teacher must orchestrate opportunities to enable acquisition by each student of a comprehensive model of the subject, characterised by a wealth of different types of relationship. If the teacher's endeavours are to lead towards what might be described as *quality learning*, students should be encouraged to gain an understanding of meta-cognition; appreciating how they learn and therefore having some control over the progress of such learning.

Although the exact contents of physics syllabi may vary somewhat, many will lead towards learning objectives such as: appreciating methods used in science, designing experiments, observing phenomena, communicating data, drawing conclusions, appreciating applications of phenomena, understanding the role of science in society and appreciating what some famous scientists have achieved. We may conclude from just a cursory consideration that this is a complex epistemology. If quality learning is ultimately concerned with understanding and, given such typical syllabi, we may conclude that the successful student is required to acquire a rich array of different types of knowledge which may be interrelated in many different ways. Whether abstract concepts can be acquired by students, or alternatively Lemke's ideas are true that concepts are developed contextually, we would wish the students to develop their own cognitive framework of interrelated knowledge which may be used to interpret phenomena and solve particular types of problem.

Unfortunately, as noted by Linn and Hsi (2000), research points to the conclusion that much of students' apparent learning in science is transitory, and many fail to develop appropriate conceptual understanding. The consequence of this being that, as observed by Thornton (1999), even students in well thought of universities are unable to solve many physics problems and fail to agree with professional physicists in answering the simplest conceptual questions. This is not a problem that can be easily solved; indeed there are many possible factors which may be primary causes. Even if not the primary cause, the teacher's knowledge of the subject and PCK must be contributory factors.

There are of course many societal factors which may greatly influence what a student learns, since society at least partly dictates where and when the learning takes place. Of course learning takes place both inside the learning organisation, e.g. a school, and in the students' everyday life. It is frustrating to realise that the majority of students are first introduced to science in a formalised, pedagogical setting, such as a school, instead of the world of practical problem solving. Many students are unable to filter out the school and see the subject in its own right. Given a society which places great stress on the continuous acquisition of qualifications, it is not surprising if many students consider success in assessment as the goal of any course. If real understanding of science means that the student must build quite complex concepts as well as acquire relevant skills, then clearly for many students this may take some time. Given a course's limited duration and the bias towards assessment based on knowledge of facts, it is again not surprising that some students will only acquire shallow knowledge. Over the last 50 years the status of the teacher in British society has plummeted. Despite this there are many dedicated and creative teachers who are successful in influencing their students to gain a real understanding of science. The role of the scientist in our society may be greatly misunderstood. Despite this, understanding and using scientific ideas is vital to the growth of many of our industries and impinges on many of our lives.

A constructivist approach to teaching and learning may well enable many students to acquire a deeper and richer understanding of science. It is interesting to note that a *constructivist* pedagogical approach subsumes the major concepts of *constructionism.* Constructionism shares with constructivism the fundamental idea that learning requires the building of knowledge structures, in fact personal ones. Following on from his pioneering work on the teaching and learning of mathematics, Papert (1972), who introduced the term constructionism, considered the importance of encouraging the learner to construct their own meaningful structures. Basing his ideas on earlier work by Piaget, he considered that this construction led to enhanced learning when learners were consciously engaged in constructing what he termed a *public entity*. Such an end product, which had a recognisable focus and a physical component, was related to the conceptual knowledge being constructed by the learners. Many readers will be familiar with his projects based on the use of physical and mathematical modelling, e.g. the use of the computer-based language LOGO for drawing and controlling movement of a robot. However, his ideas on learners designing and constructing may be applied to any subject. As a pioneer in post-constructivist pedagogy and in AI, he still has a great deal to offer the novice teacher and he currently holds the position of *Lego Chair* at MIT, a position created for him in recognition of his work. Although he was not satisfied with some people's definition of constructionism as a type of constructivism, but differentiated by "learning by making", Papert (1991) playfully suggested that it would be against his constructionist learning model to impose a definition of the term. Instead, he suggested that teachers or researchers should construct their own understanding of such a pedagogical concept .

For the perhaps more experienced physics teacher Papert's work on constructionism contains several very interesting and potentially fruitful pedagogical ideas which cannot be described just in terms of "learning by making". Learning may be favourably influenced by exploiting factors, which might be termed here, *play* and *pattern.* Papert (1991) considered the importance in a learning-rich activity of the perception of patterns, in particular recursive patterns. The recognition that one object is fabricated from, or defined in terms of, smaller or simpler versions of the same object, is a familiar concept in many subjects including art, mathematics, computer programming and science. To be able to recognise that two objects have some measure of similarity, or are in some fashion opposite, is an essential pattern matching skill for the physicist or physics student. It could be argued that all construction requires an understanding of pattern, similarity and, as considered in an earlier chapter, abstraction.

Despite occasional efforts by television producers, professional bodies and others to popularise physics, it remains to many in the wider population, a difficult and boring subject which has little to do with people's everyday lives. Unfortunately this view may affect a student's choice when selecting subjects to study further. However, given adequate time and knowledge, an enthusiastic physics teacher may design learning activities which show that the subject can be very enjoyable. Papert's ideas on the element of play in creativity can be fruitfully applied in many different ways in the classroom or laboratory.

Physicists too have found that interesting ideas may emerge through playing with concepts, however bizarre this may first appear. A physicist may consider moving an observer to a new privileged position in an *armchair experiment*; as Einstein did when considering an observer moving with a beam of light. Flattening space by removing one of the three spatial dimensions helps to solve some vector analysis problems. Even resurrecting Isaac Newton and allowing him to question modern innovations can prove to be a rewarding playful learning activity.

An earlier chapter considered the importance of context when building an understanding of a physics concept. Through familiarity with a particular narrow branch of physics, the professional physicist may base his or her procedural knowledge on a distilled version of the underpinning concepts. In the limit, the physicist may make use of just the mathematical abstraction and begin to describe the particular phenomenon in purely mathematical terms. However, in reaching this specialised position the physicist will have used a richer abstraction as an integral part of the knowledge construction or concept acquisition process. Once it has been shown to be useful in understanding a new phenomenon, a chosen type of abstraction becomes associated with that phenomenon.

However, it has proved to be creatively fruitful to consciously apply an abstraction found to be valid in one context to a new context. This process deliberately divorces one aspect of a pattern, i.e. the abstraction, from its usual context and reapplies it in a novel context. The result of this *what if* exercise may lead towards a deeper understanding of the concepts behind the new context. For example, the concept of phonons and modern micro-acoustics emerged from applying an abstraction to help explain one phenomenon (namely photon transmission) to a new phenomenon (transmission of sound). Reapplying an abstraction in this way may be considered as changing its contextual role.

Applying an abstraction in a new context may be of use in conceptual learning, however there are potential pedagogical problems if such a role change is taken to extremes. One such extreme is that of anthropomorphism, the attribution of human characteristics to non-human objects. This is most commonly observed when physics students use metaphorical language to explain physical phenomena, as in "… the electron *sees* the positive electrode and *must obey* the law of attraction of opposites". Such language may be acceptable if no other abstractive language is available to the learner and the explanation leads to a valid conclusion. However, the physics teacher may wish to encourage students to begin to use less anthropomorphic terms which tend to disguise the real nature of *cause and effect* in the phenomenon.

Obviously a constructivist approach requires that adequate time and energy be applied if the aim is to change students' conceptual understanding. Relatively recently, several researchers interested in science teaching (Strike and Posner, 1992; Linn and Hsi, 2000; Kallery and Psillos, 2004), drawing upon earlier ideas by Lemke (1990), have considered the importance of knowledge integration. In order for the student to acquire understanding of the nature of physics, learning must involve investigation of what Linn (1995) described as "… extensive linkages between elements of knowledge". An integrated network of knowledge may then be used to interpret particular phenomena. There is disagreement regarding the exact nature of how knowledge integration may take place. However, there is some agreement that when the student is dissatisfied with their current explanation of a phenomenon, and they have reasons to take on new ideas, they may begin to reconstruct their current conceptual framework (Ausubel, 1963; Linn, 1995; Blackwell, 1998). Thornton (1999) similarly argued that existing cognitive structures are reorganised to assimilate new learning experiences. However, he did advocate the use of what he termed *advanced organisers* which might aid the mechanism through the application of higher level abstraction techniques.

In a constructivist learning environment for physics, developing students' integrated knowledge may begin by realising that students bring with them to the science classroom or laboratory various beliefs about phenomena and alternative concepts, called by some *misconceptions*, (Linn, 1995). Again, by giving them more control over their own learning, students may be encouraged to challenge these preconceived ideas in the light of what is being taught. This clearly requires even the novice teacher to encourage the development of inquiry through dialogues (Gess-Newsome, 2002). However, an inexperienced physics teacher may not have yet acquired enough useful PCK to feel confident in allowing students to hold, and argue to support, invalid concepts. Furthermore, if the teacher lacks the depth of understanding of the nature of science and of concepts in physics, there may be a tendency to stay with a less student-centred pedagogical approach. This was clearly identified in the relatively recent OFSTED report which stated:

> *"When teachers are thoroughly in command of the subject, they are able to adapt their teaching to the responses of the pupils, to use alternative and more imaginative ways of explaining, and to make connections between aspects of their subject and the pupils' wider experiences, so capturing attention and interest"* (OFSTED Report 1998).

Unfortunately pre-service physics teachers may themselves have invalid views on the nature of science or may adhere to misconceptions. This will hardly put them in a position to creatively challenge their students' unscientific ideas (Kallery and Psillos, 2004). Several research projects over the last 40 years have indicated that pre-service science teachers may have simplistic views of the nature of science, but these views may be successfully challenged. Ausubel (1963) had some success in influencing pre-service science teachers away from defining science in terms of a body of knowledge towards a more accurate view which incorporated the role of scientific processes. This was found to be possible through moving the focus of the teaching away from verbal and textual presentations of information to be learnt, towards a more laboratory-oriented approach. More recently Eick (2000) found that there was an increase in a positive attitude towards science when students considered the history of science, where they were introduced to role models, and greater focus was placed upon how scientific concepts become incorporated into an organised dynamic framework of knowledge.

Of course the question arises concerning how pre-service physics teachers might be encouraged to question their current understanding of the nature of science, as well as their knowledge of physics concepts. Interestingly, Beatty and Gerace (2002) argued that the development of more complex conceptions of the nature of science would play a vital role in developing more complex PCK for its teaching. However, developing one's own complex conceptions of a subject such as physics is not something that can be done quickly and without support. Might a professional physicist have a role to play in describing to school students his or her practical, research-oriented view of a particular aspect of physics? Would it be beneficial to know how an experienced physics teacher sees how their PCK relates to the particular concepts being taught? The computer has been used to help in the teaching of physics for many years. Could it now be used to represent something of the complex interrelationships between concepts, above and beyond that represented by simple *concept map* software? The answer to all these questions is of course "yes".

Chapter 6

METAPHOR AND ANALOGY IN TEACHING PHYSICS

Humans are adept at recognising certain types of pattern from sense data. We do not simply gather data and then impose meaning on it such that it becomes *information*. Instead we perceptually seek out particular types of correlation (Ross, 1989). Thus it may be that our brains have evolved to be more efficient by performing a type of internal semiosis, whereby complex input is classified according to its attributes and represented by a briefer, attribute-based summary. Such a semiotic view of the development of concepts is by no means at odds with Bohm's ideas (Bohm, 1965) on the close relationship between perception and abstraction mentioned in an earlier chapter. Understanding the physicist's worldview, and being able to help students understand it, requires the novice physics teacher to realise the nature of the patterns and logic behind the modelling of physical phenomena. Bohm in his usual succinct style considered that physics was concerned with discovering *invariance*. Identifying the circumstances when particular measurable phenomena do **not** change is the primitive, foundational pattern on which to base experiments and observations in order to identify other layers of pattern.

Physics is concerned with understanding and hence explaining the physical world. This process often begins with the observation of an interesting physical phenomenon. Then may begin an investigation into the relationships between the various observable parameters, associated with the phenomenon. Supported by a belief system based on causes and effects the physicist will invariably begin to develop a conceptual model of what may be happening to produce the phenomenon. Such a model may then be used to predict the behaviour of the phenomenon when particular causal factors are changed. Experiments may then be devised in order to test the validity of the explanatory model. Experimentally measured parameters are compared with those predicted by the model. Subsequently the model is revised and the process repeated. The physicist may devise a whole series of experiments where earlier versions involve cruder measurement techniques, e.g. observing a colour *change*. Later experiments will be more qualitatively accurate involving careful measurement using accepted comparative units, e.g. observing that light of a frequency of 550 nanometres changes to a frequency of 620 nanometres. The cycle of *observation of a phenomenon, refinement of a model, prediction of changes, design of experiment* is at the heart of physics and of course should be at the heart of physics pedagogy.

The professional physicist working in a team has a similar problem to solve as that of the physics teacher; that of how to describe the conceptual model which has been devised to describe the phenomenon. Although the team of professional physicists will more often rely on mathematical models, there are occasions when they and the physics teacher rely on an *analogy* to explain their ideas. The professional physicist will attempt to adapt and reuse an existing model with which the whole team is familiar. Understanding the new phenomenon, or more succinctly understanding how the particular physicist envisages the new phenomenon, may be helped or hindered by using a previously accepted model. The use of an existing analogy, or perhaps at times a more colourful metaphor, represents a complex and interesting type of abstraction. The use of analogies and metaphors are an essential part of PCK for physics teachers as well as teachers in many other subjects.

The word metaphor comes from the Greek word *μεταπηορα* (*metaphora*), meaning to convey or transfer. Although it might be argued that metaphors are essentially types of analogies (Gentner, Bowdle et al., 2001), physicists would normally use the term analogy to refer to an explanatory model, whilst metaphor, if used at all, would refer to particular words or phrases used to help explain some concept.

This does not mean that metaphors are unimportant to the physics teacher; they are still an important type of abstraction. Paivio and Walsh (1993) considered that metaphor is the most striking evidence of what they termed *abstractive seeing*. In attempting to understand aspects of the world, and communicating this to others, we use what they termed "our presentational symbols". Although these are cognitive structures, for the physics teacher they may be related to physical forms. Therefore the use of metaphors in physics pedagogy is essentially a form of semiosis.

The teaching of physics would no doubt be easier if the teacher and the student shared a common language. They do of course share a common subset of written and spoken language, e.g. everyday English. However physics, like many subjects, relies on a wealth of specially designed terms, some of which have been adopted by most English speakers (e.g. electronics, vacuum, thermostat), while others are only used by physicists (e.g. quark, maser, thermoluminescence). Perhaps the most problematic case of language use is when a reasonably common word or phrase is reused by physics in a more focused and specialised context (e.g. cell, resistance, mass). Careful choice of such language terms may facilitate the correct understanding desired by the speaker (Parida and Goswami, 2000), but when explaining things in written or spoken form we must be on our guard constantly asking whether the chosen words or phrases might be misleading to the students. In cases when using a metaphorical term, we expect the listener or reader to reject the literal meaning of the word or phrase, and then make a semantic mapping between the attributes of the concept brought to mind by the metaphorical term with other attributes within the concept being metaphorically modelled. This is clearly a complex process requiring considerable linguistic experience on the part of the listener or reader. Medin and Ortony (1989), reporting on the inability of students to solve verbally presented problems, observed that many were unable to interpret the various verbal clues in the description.

Some metaphorical terms commonly used by the physics teacher may become conventionally associated with the concept being explained. There are times however when the listener or reader may be confused about which attributes of the metaphorical model should be used as sources of mappings; which will lead to a better understanding of the concept being modelled or which should be rejected. For example, it is common to physics teachers and physics textbooks to use a phrase such as the *flow of electrons* to explain something about the nature of an electrical current. We should not be surprised if the physics student therefore asks questions related to electrons as fluids, such as "do electrons flow around the atoms, or through them?".

With experience a physics teacher should be able to identify which are the metaphorical terms which help a particular group to learn, and which terms to avoid. A teacher's PCK concerning the use of metaphorical language may also make use of the reverse mapping; therefore investigating whether the metaphor has particular properties which are associated with newly found attributes of the concept being modelled. With a group of students who have adequate linguistic skills this might lead towards creativity and deeper understanding not just of the concept being modelled, but of the use of metaphors in learning. Hence it might be used to teach some meta-cognitive skills.

The physicist and experienced physics teacher make use of a wide spectrum of different types of model to help in explaining concepts and in solving problems. In every case the particular properties of a model are related to corresponding properties of the system or concept being modelled. If the use of the model is to be successful the properties of the model and of the system being modelled must also relate to particular features of a conceptual model which the teacher wishes the student to develop. The chosen model may be physical (e.g. a Victorian *orrery* which was a popular way of explaining how the planets orbit the sun), diagrammatic (e.g. representing electrons in elliptical orbits around an atom's nucleus by coloured discs), verbal (e.g. describing how Bohr's concept of electrons orbiting an atom's nucleus relates to planets orbiting the sun). In each case, careful use of the model may help students to acquire concepts; but their use is not without possible problems.

Analogies or analogical models have been used to a certain extent throughout the history of physics. Reasoning based on analogies is considered by some to be ubiquitous (Mayer, 1992). In an analogy a comparison is made between two different domains of knowledge, one of which should be familiar, the so-called *analogue* domain, and one which may not, the *target* domain (Collins and Burstein, 1988; Bransford, Franks et al., 1989; Vosniadou, 1989; Tripp, 1997; O'Donoghue, 1998; Melis and Veloso, 1999; Orgill and Bodner, 2004). One analogy that is familiar to most physics teachers is Rutherford's analogy between the solar system (analogue domain) and the hydrogen atom (target domain). It will be effective as an analogy provided the student has appropriate knowledge of the solar system and can relate certain aspects of the analogue domain onto the target domain. Several authors concerned with science teaching (Thiele and Treagust, 1995) consider that when selecting an analogue domain in order to try to explain the nature of the target domain, preference should be given to one which shares more of a structural or relational similarity with the target domain, rather than just sharing attribute or superficial similarity. Gentner and Jeziorski (1998) considered the nature of the mapping between analogue and target domains in successful analogical cases. They posited what they called the *principle of systematicity*, which in essence was that people prefer to map systems of predicates governed by higher-order relations with inferential import, rather than to map isolated predicates. They concluded that their systematicity principle reflected tacit human preference for coherence and inferential power in interpreting analogy. In the case of someone being presented for the first time with Rutherford's solar system analogy, provided that they have sufficient knowledge about the solar system, must find a set of relations common to the analogue and the target domains that can be consistently mapped and that is as deep, i.e. as systematic, as possible. The deepest relational system that is common in this case is that pertaining to satellite motion which is caused by a centrally originated force. Other isolated relations, which obviously do not belong to both domains, such as the sun being hotter than a planet, are disregarded. The attributes of individual objects, e.g. the colour of the sun, are also disregarded. Correspondences between objects that are not disregarded are those such as: sun mapped to nucleus, planet mapped to the electron.

When considering the selection of analogue domains for pedagogical use, Piaget (1962) identified that selecting what he termed a *productive analogue* cannot be based on the explanation structure of the two systems. It must be based on similarity of easily accessible properties between the two systems. With the solar system analogy we expect the student to use the same mental image to represent the analogue domain and the target domain. Therefore both domains should have structural similarity and perceived using similar levels of abstraction. However, continued success of this analogue in the physics classroom may depend upon similarity of causal relationships. Through discourse the teacher may encourage students towards an understanding that a force must exist in both domains in order for the satellites (electrons or planets) to continue in their orbits.

There is substantial evidence to suggest that the use of analogy is particularly useful in problem solving. Analogical reasoning enables us to infer some aspect of the target object from the knowledge we have about the source object (i.e. an object in the analogue domain). When applying analogical reasoning to problem-solving we seek to infer the solution of the target problem from knowledge about the solution to a source problem because of its similarity to the target problem. Many authors have concluded that appropriate learning in science could indeed be promoted by using analogies; helping students to relate new knowledge to already acquired concepts. Several such authors concluded that their evidence supported a constructivist view of learning. Some authors have gone further by suggesting that analogical reasoning is central to all problem solving (Cunningham, Duffy et al., 1993; Hadamard, 1996), and even ventured to suggest that it is a ubiquitous process and one of the most fundamental aspects of human cognition (Carreira, 1997).

Analogical reasoning is only valid in cases where there is some recognised similarity between analogue and target domains. Recognising how two things are similar is a fundamental aspect of classifying the physical world. Therefore being able to aid students in the discovery of similarity is vital PCK for the novice physics teacher. Analogical reasoning, that is reasoning on the basis of similarity, is an essential form of human reasoning. Indeed, Mayer (1992) identified it as being the main form of reasoning for young children. Several authors have postulated models for corresponding reasoning mechanisms. Medin and Ortony (1989) introduced the concept of a *generalization mechanism* which would automatically act on instances to produce less context-bound generalizations. However, Gentner, Bowdle et al. (2001) argued that human reasoning does not always operate on the basis of content-free inference rules, but may be tied to particular bodies of knowledge. Therefore in part, learning involves identifying the most relevant knowledge domain. These ideas of course would support Lemke's view on the existence of context-related concepts as opposed to abstract concepts.

Many science teachers find it useful to teach something of the history of science (Eick, 2000). This may give students a clearer understanding of the role of the scientist in society (Gess-Newsome, 2002) as well as explaining something of how scientific knowledge is developed. Discussion will invariably focus on certain famous scientists whose seminal research and invention has contributed considerably to our present understanding. The physics teacher may find it useful to discuss ways in which reasoning may lead to creativity and that even students may be inventive through application of certain techniques. Taber (2001) among others considered that analogical reasoning was such a technique. Paivio and Walsh (1993) considered that a scientist could make an intuitive analogical leap by transporting a familiar idea into a novel arena; giving as an example the introduction of the concept of a phonon derived from that of a photon, as considered in an earlier chapter. In a similar manner Carreira (1997) considered creativity to be a search for an analogue with which to interpret a given target domain.

The use of analogy in physics teaching is not without controversy. Although Mayer (1993) found that analogues did help students understand scientific explanations of how things work, he quite rightly pointed out that such analogies might have no positive effect on the learning process at all. Indeed, the use of an ill chosen analogue might even direct the learner's attention away from the vital information, instead of encouraging the learner to build appropriate cognitive structures. Experience suggests that choosing simpler analogues may be less problematic. Being able to select an appropriate analogue through identifying relevant similarities between analogue and target domains is an important stage in the development of the novice physics teacher's PCK. Unfortunately there is evidence to indicate that the perception of similarity differs between experts and novices. Novices tend to focus more on those attributes of the two systems which may be immediately observed by the senses. Ross (1989) and Vosniadou (1989) both found that students easily recognised superficial similarity, but often found it difficult to abstract out structural similarities. It is evident therefore, that both physics students and novice physics teachers may have to be presented with many simple analogical cases to enable them to build their own versions of this important modelling skill.

There is evidence to indicate that students find difficulty in applying analogical reasoning to a new problem on the basis of recognising similarity with an earlier problem. This may be the case even where the new problem is remarkably similar to the earlier one. This may be due to an inability to extract salient features of the two problems or an inability to recognise similarity between them. Such evidence may indicate more validity to Lemke's views concerning the development of context-based concepts (Lemke, 1994). It may also indicate dynamic, evidentially led development of concepts; where the development of less context-oriented concepts requires the use of a large number of cases of varying similarity.

There are other factors which may affect a student's ability to use analogical reasoning when solving problems. Students can be very creative and, as Tripp (1997) identified, some are prone to infer interesting, but perhaps invalid, conclusions from evidence they receive.

Chapter 7

CONSTRUCTIVIST LEARNING

The behaviourist theory of learning, popularised by B. F. Skinner (1968), was very influential in science teaching for much of the latter part of the last century, its claims have been questioned in the light of research in several subjects including cognitive science. Behaviourist theory influenced the design of tightly sequenced science curricula in response to the belief that it was appropriate to get students to master small amounts of knowledge before integrating them into concepts. The theory also influenced the design of assessment to focus more on measurement of learnt facts and basic skills, rather than on deeper understanding. Although perhaps not the intended function of behaviourist-based learning, students were considered to have mastered knowledge if they were able to reproduce ways of representing that knowledge, for example in the form of stating definitions. Some students were able to use this learning as a step towards deeper conceptual understanding, although many were not. Therefore the theory might be criticised as only being valid when students learn by rote and acquire surface knowledge.

Behaviourism has been criticised by many as an epistemology as well as a foundation for pedagogy. It views knowledge to be inert and transmittable, with students basically being passive receivers of that knowledge (Tobin, 1993). In contrast to this, the constructivist theory of learning considers that knowledge cannot be transmitted from teacher to learner, but has to be actively acquired, self constructed and personalised. Hence the exact meaning each individual learner derives from a particular experience is unique (Jonassen, Davidson et al., 1995).

As part of this thesis computer software has been designed to aid in the understanding of one aspect of the PCK of an experienced physics teacher. In keeping with Bruner (1966), the design of this software and recommendations for its use are strongly related to a particular view of learning science, namely constructivism.

The constructivist view of learning is that the learner constructs new knowledge based upon prior knowledge and experience (Garrison, 1992). Fosnot (1996) considered that learning occurs by synthesising new information into existing knowledge and adjusting prior understandings and beliefs to assimilate the new experience. To make fuller sense of experience, learning must be socially-mediated (Jonassen, 1991) through discussion and problem solving (Forman and Pufall, 1988), within a community of practitioners (Piaget, 1973). Hence, according to Vygotsky (1962) in the constructivist view of learning, the learner has two responsible roles; that of constructing meaning from experience, together with justifying that meaning through critical discourse.

A most succinct view of constructivist pedagogy was coined by Catherine Fosnot (1992) as "...new experiences sometimes foster contradictions to our present understandings, making them insufficient and thus perturbing and *disequilibriating* the structure, causing us to accommodate. Accommodation is comprised of reflection, integrative behaviour that serves to change one's self and explicate the object in order for us to function with cognitive equilibrium in relation to it".

The subject of constructivism today is now complex. It constitutes a broad theoretical framework representing a wide spectrum of beliefs about the nature of learning (Scardamalia and Bereiter, 1993; Tobin, Tippins et al., 1993; Scardamalia and Bereiter, 1994) and some authors consider that it partially explains how individuals think and create their own meaning (Jonassen, Davidson et al., 1995).

Piaget is considered to be one of the foremost adherents of constructivism, however the theoretical foundation of this thesis owes much to the work of the eminent Marxist psychologist Vygotsky (1962; 1987; 1988). Vygotsky (1987) considered constructivism as a theory of cognitive growth and learning, and that learners actively constructed their knowledge through the mediation of societal structures. To him we humans have always invented cultural tools, both material and psychological, creating a cognitive technology to restructure our abilities and reconfigure our very nature. His view was that understanding itself is social in origin: learning is mediated through tools in society. Others have re-emphasised that learning is a socially-mediated process of making sense of our experience (Mead, 1934). Within a learning community, meaning is negotiated (Piaget, 1932, 1970).

Vygotsky (1987) considered that language was the most fundamental form of societal mediation, but he also recognised the use of a vast range of semiotic and psychological tools; including counting systems, mnemonic techniques, algebra, works of art, writing, schemae, diagrams, maps, technical drawings etc. He considered that artefacts transformed mental functioning in fundamental ways. They did not simply serve to aid mental processes that would otherwise exist. Instead they fundamentally shaped and transformed them (Valsiner, 1993; Wozniak, 1993). Psychological tools enable us to link lower and higher mental functions (Vygotsky, 1978).

Leontiev (1981) considered that of the psychological tools that "mediate thoughts, feelings and behaviours", language was the most important; "a tool of tools". As language constructs reality, so symbolisation constitutes objects. "Symbolisation constitutes objects not conceptualised before, objects which would not exist for the context of social relationships wherein symbolisation occurs. Language does not simply symbolise a situation or object which is already there in advance; it makes possible the existence or the appearance of the situation or object, for it is part of the mechanism whereby that situation or object is created"

There has been some controversy over differences in how Piaget and Vygotsky viewed the roles of individuals and society in learning. Piaget did not himself deny the role of the social world in the construction of knowledge. Neither did Vygotsky (1978) deny that active construction of knowledge by an individual was central to cognition. However, Vygotsky emphasised the important *complementarity* between the active individual learner and the active social environment (Donaldson and Graham, 1999).

In the 1920s and 1930s, Vygotsky and his colleagues Leontiev and Luria introduced a theoretical concept known as Activity Theory. This was in response to the behaviourist psychological theories of the day. Not a theory in the exact sense of the word, Activity Theory is a conceptual model of artefact-mediated action on real world objects, on which theories may be based. Building on Vygotsky's work on constructivist learning, Activity Theory stressed the relationship between human agents and objects in the environment, mediated by cultural means, tools and signs. Its first tenet was the principle of "unity and inseparability of consciousness and activity". It was believed that the human mind comes into existence and develops, and can only be understood, in a context of goal-oriented, socially determined interaction between groups of humans and their objective (material) environment.

The five basic pillars of Activity Theory are its objective (material) basis, the interplay between internalisation and externalisation, tool-mediated interaction, the hierarchical structure of activity, and continuing human development. As the theory has a materialist basis it considers that the objects in reality have properties and are objective according to natural science, but also have accepted socio-cultural properties. The theory stresses that internal activities (mental processes) cannot be understood if analysed in isolation to external activities. There are mutual transformations between the two sets of activities: internalisation/externalisation. It is the context of activity, including both internal and external components, that determines when and why external activities become internalised and vice versa.

Muth and Guzman (2000) considered that the analysis framework for social activities identifies that activities, actions and operations performed by the various social participants reveal their motives, goals and instrumental conditions respectively. Leontiev (1981) had considered that the concept of activity corresponds to the active agent's specific need: it moves toward the object of this need and terminates when the need is satisfied. Hence the concept of activity is directly connected with the concept of motive. Activities are translated into reality by a corresponding set of actions used to test a conscious goal. Leontiev considered therefore that activities and actions are separate but associated realities: a particular action can lead to different activities; on the other hand, a particular motive can lead to different goals and therefore produce different actions. Actions are developed through operations which are concerned with conditions. The distinction between actions and operations emerges clearly in the case of actions involving tools: while actions are connected to conscious goals, operations are related to routine behaviour performed automatically, hence using a different level of consciousness.

Any learning environment, including one mediated by computer software, which purports to be based on constructivist thinking, should encourage learners to construct their own context-based knowledge through real world or case-based tasks, lead to reflection and emphasise collaboration between students (Hermann, 1995). As well as being validly used in schools, there are several factors which favour the use of constructivist learning environments within Higher Education. The proportion of mature students is increasing, and providing such students understand why they are studying, they may bring a wealth of experience into any learning group. Mature students seem to flourish when using creative ways of enhancing their education, allowing them to make conscious links between their *real world* experience and new knowledge. Naturally they wish new knowledge to be relevant, hence directly applicable (Pea, 1994). A constructivist learning environment, accessible from a campus or via the World Wide Web, may refocus the emphasis from tutor to learner, and may provide a rich resource of domain-based knowledge for self-directed, collaborative learning (Pea, 1994). Following on from the ideas of Vygotsky and others that tools are mediating devices in learning, several authors have considered the impact of mediating tools on learning within systems using computers. Muth and Guzman (2000) for example recognised that some common types of software (e.g. electronic mail) may have a role to play in asynchronous learning, acting as socially mediating tools or artefacts.

Relying more and more on the use of computers as mediating learning tools is not pedagogically trouble free. The development of the World Wide Web has meant that students are now able to quickly search for information, but there is no guarantee that the information is relevant or even true. The ubiquitous nature of access to the World Wide Web means that so called *distance learning* is becoming feasible. There is however a very worrying trend amongst some advocating the wider use of computer-based learning, especially in Higher Education. In a response to the governmental request for what is termed *widening participation,* universities and colleges are considering non-traditional ways of delivering teaching to a geographically wider audience. Unfortunately this is often interpreted as merely finding cheaper ways of delivering information to students over a campus-wide network or the wider Internet. Replacing the type of lecture characterised by the one-way communication between lecturer and note-taking students, by a computer-based information delivery system, is perhaps pedagogically valid. On the other hand, no currently available computer system is able to replace the flexible teaching style common in tutorials and more interactive lectures or classes. Reducing the face to face contact time between students and tutors may enable *full-time* students to be employed to support their learning, but there are obvious pedagogical consequences. Only the better students can turn delivered data into meaningful information, then use that information for the construction of knowledge without adequate interaction with students and tutors. Therefore, there may be a tendency for some students to acquire only a shallow understanding of a subject. The final consequences may be that either educational standards are reduced to maintain pass rates, or only the fewer gifted students are retained on courses; which of course is totally opposite to the government's objective of widening participation.

Many authors have stressed the primary importance of conversation within group-based learning. Within learning systems in general, conversations between learners have been categorised within the hierarchy: transactional, transformation and transcendent (Pea, 1994). Transactional conversations, also termed academic conversations (Bereiter, 1994; Hermann, 1995), or transmissive conversations (Sherry, 1998) are mutually valued, for example in the transmission of knowledge. Transformational conversations take place when participating students are able to set aside their preconceptions, listening and engaging in mutual dialogue. Transcendental conversations, termed transformative conversations by some authors (Jonassen, Davidson et al., 1995) occur when learners use dialogue to affect change (Harasim, 1990). It is considered that in its deep cognitive level transcendent (Oblinger and Maruyama, 1996) conversations differ from transmissive conversations, where knowledge is transmitted, and from ritualistic communication, which uses symbols to represent that knowledge.

When designing a modern computer-supported learning environment, the quality of interaction between users must be considered as important as the delivery of multimedia data. Through using appropriate computer-based systems for learning, the level of conversation can be altered when allowing students to enter into dialogue with their peers and with tutors. This may enable the construction of shared meaning through community-building dialogue. The student may suppress their isolated, individualised thinking and take an active part in a common purpose group to negotiate a shared set of meanings

(Pask, 1975). This type of educational dialogue can transform the individual and help to create a longitudinal community, which can share mediated resources of knowledge, relevant experiences, insights, beliefs and assumptions (Harasim, 1990; Warschauer, 1997).

Using computers may change the very quality of student communication through allowing time for critical reflection (Wells, 1993; Greto, 1999). This may enable more students to discuss topics more deeply than in traditional tutorials, where often just the same few students monopolise the conversation (Wells, 1993; Olcott, 1994). Some authors found that using written text-based mediation developed higher quality work because students' words were visible to their peers (Jonassen, Davidson et al., 1995). Pask (1975) introduced a dialectic model for the construction of knowledge when applied to learners in conversation. His model, *conversation theory*, agrees essentially with the ideas of Vygotsky. Pask's work relates to operant conditioning tools introduced by Skinner. Pask agreed with Vygotsky that learning is by its very nature a social phenomenon; new knowledge again is constructed out of the interaction of people in dialogue, and that learning requires the learner to test a personally held concept against that of another until agreement is reached.

The use of computers has been seen by some as an important basis for constructivist learning as it enables collaborative working. It may give students a greater role in the collaborative group (Sharan, 1980; Oliver and Reeves, 1994) and help the more shy or reticent student (Harasim, 1990). Even the role of the tutor may change, migrating from domain expert towards facilitator (Jonassen, 1994). There is also evidence that the use of computers has helped in building group coherence (Papert, 1993).

With the students working actively and collaboratively through the mediation of computers, they can be invested with the responsibility for the acquisition of new knowledge. Hence, within such a collaborative environment for constructivist learning, there is a requirement for peer interaction, evaluation and cooperation. Indeed, students may achieve greater cognitive development working together than they would do when working individually (Hannafin, 1992). There is evidence that in a constructivist learning environment where students share information and use collaborative learning strategies, the student group may enhance their expertise and problem solving ability (Collins and Burstein, 1988).

When considering the use of computers in a learning environment where constructivist thinking can take place, several researchers have considered the importance of having multiple representations of reality (Lave and Wenger, 1991; Bechtel, 1993; Cole and Engstrom, 1993; Hutchins, 1995). Clearly today this may be possible due to the multimedia potential of Internet/intranet-based resources.

Papert (1991) coined the term *constructionism* when considering his version of constructivist learning. To Papert active construction of computer based, educational systems by students was vital. "It is through the construction of educationally powerful computational environments that will provide alternatives to traditional classrooms and traditional instruction". He understood the future role computers would play in education where they would create rich, adaptable environments to enable informal constructivist learning. "... computers serve best when they allow everything to change ... I am convinced that the best learning takes place when the learner takes charge ... knowledge is constructed, not absorbed. Children do not get ideas, they make them. ... they make ideas best when they make personally meaningful artefacts, on which to reflect and discuss".

Ryder (1994) suggested that the Internet could be a powerful constructivist environment for learning. As a virtual library its abundant information resources could organically grow in response to human participation. He envisaged that learners would enrich the information they had found. Hannafin (1992) considered that the World Wide Web was a fertile, generative environment allowing the creation and enhancement of knowledge. The Internet offers the type of social interaction between learners stressed by Vygotsky. Corresponding to his *zone of proximal development*, which represents the cognitive distance between the learners' individualised, actual development, and the potential development emerging through an interaction, learners can grow into the intellectual culture taking a deeper role in the practitioner community. Even the relatively passive, Internet-based learner through observation may pick up relevant jargon and discover established practice of a community.

Vygotsky's arguments that learning is mediated by socially related tools is echoed in the concept of distributed cognition and situated learning (Matthews, 1994; Trotter, 1995; Osborne, 1996) where formalised symbols are located within a computer-based learning environment. The Internet when used by school students or undergraduates becomes a system which may be recognised as a socio-cultural, semiotically-mediated system where constructivist learning may take place. Activity Theory may then enable a better understanding of the interaction between members of the learning community and the Web-based tools. Along these lines some authors have indeed applied Activity Theory to Human Computer Interaction (HCI), although not specifically using the World Wide Web, as the foundation for a learning environment (Wang and Cox-Petersen, 2002). Such researchers have identified in HCI that operations do not have their own goals; rather they provide an adjustment of actions to current situations. Tools are created and transformed during the development of such activity itself and carry with them a particular culture; a recognised behaviour of Web-based users.

As we move beyond the use of computers in education as just a means of sending and receiving data, there is a need to carefully consider the changing role of the teacher, especially within a constructivist learning environment. The most important objectives for the teacher in this context is to help students to construct knowledge rather than reproduce a set of facts. Although quite rightly pointed out by Chang and Sung et al (2003), this does not remove the active role of the teacher, nor devalue his or her expert knowledge. Ensuring student understanding requires active student involvement in the process of learning. As pointed out by Taylor and Geelan et al (1997), among many others who have written on constructivist learning in science and mathematics, the students' knowledge can be actively tested through problem solving exercises and practical work. This process can begin on the very day that a physics course begins, since all students will arrive with their own theories about the physical world acquired through their everyday experiences. Bannan-Ritland and Dabbagh et al. (2001) considered that lying at the heart of constructivism is the marriage of two distinctive metaphors for learning; namely *acquisition* and *participation.* The acquisition metaphor regards learning as the act of gaining knowledge by developing concepts. Concepts, considered as a basic unit of knowledge, can be accumulated, elaborated, refined and combined to form a cognitive structure. On the other hand, the participation metaphor considers learning as a process, hence focusing on knowing rather than knowledge acquisition. It is seen as an ongoing activity which is not separate from the context in which it takes place, therefore learning is understood in this metaphor as the process of becoming a member of a certain community of learners, through discourse. The synthesis of these two metaphors would seem to be a vital aim for the physics teacher.

Several authors (Bednar, Cunningham et al., 1992; Hannafin, 1992; Merrill, 1999) have considered that the teacher must provide appropriate conditions to enable students to construct their own knowledge. Therefore the teacher must exploit each and every opportunity to focus the observation and discourse of the group of learners towards a valid interpretation of phenomena. Alternatively, invalid interpretations would have to be challenged through logical discourse or experiment. As Riddle, Pearce et al (1997) pointed out, students are willing to accept new interpretations when they are unsatisfied with their current ideas. It may be part of the teacher's role to foster than dissatisfaction, perhaps through demonstrating that the students' current view is indeed erroneous. Without doubt when designing a constructivist learning environment the teacher must focus on the student's active participation in the learning process. But as pointed out by McLoughlin and Oliver (1998), learning environments should provide students with the experience of co-constructing knowledge as a member of the learning community, thereby understanding more deeply how themselves learn.

In teaching physics we are asking the learner to perceive particular phenomena in a particular way. As pointed out by Bohm (1965), this perception relies upon (persistent) abstraction and is refined using the cyclic process of experiment, model refinement and prediction; a scientific method which has as its goal the development of understanding. But of course, if we wish students to understand physics to other than a trivial level, it does take time. Unfortunately this view may be out of kilter with a *quick fix*, assessment oriented, educational system.

One of the most influential authors on constructivism, Ernst von Glaserfeld (1983; 1987; 1989; 1996) stressed radical constructivism as a theory of knowledge and cognition. To him knowledge was not passively received, neither through the senses nor by communicating, but was actively built by the cognizing subject. The function of cognition was adaptive, and attempted to increase viability. It served the organization of the experiential world for the particular subject. If, in a constructivist learning environment, the teacher is able to provide rich opportunities for students to build their own knowledge it does not mean that all of their interpretations are equally valid. Constructivist learning will not mean that the student eventually moves towards a position totally at odds with accepted scientific theory. Constructivist learning requires societal based negotiation, and in the case of science teaching that society comprises those learners who are testing and refining designed models through experimentation. Science does not exist as a body of knowledge separate from human scientists, or students for that matter. Knowledge becomes accepted by the scientific community as viable because of its coherence with other theories and its evidential foundation.

Educators may interpret the essential elements of constructivism differently when teaching different subjects. As McLoughlin (1997) quite rightly pointed out, constructivism is concerned with learning; it is essentially a theory of learning. Although learning takes place within a social group individuals build their own concepts. But this does not mean that students are encouraged to find their own answers without guidance. However, the science teacher should refrain from asserting accepted scientific laws, since understanding will only emerge through students incorporating new ideas into their existing knowledge. Of course this may entail radical changes to the structure of the students' current epistemology and their world view.

To Vygotsky (1987) and other constructivists, learning occurs as a result of social interaction, requiring the use of signs and symbols to enable us to communicate and think in more complex ways (Wertsch, 1991). Signs and symbols enable the mediation of meaning by a group of learners, and without them each individual would be forced to consider every experience as unique and unrelated to any other. In constructivism, appreciating the vital role played by signs and symbols in the construction of knowledge is vital to understanding the nature of human cognition.

Semiotics is the theory and study of signs and symbols, in the context of them being used in *language*; provided this term is used in its broadest sense as a *system of communication*. Although concerned with different disciplines, many authors have described language in terms of the different attributes introduced by Lounsbury (1956);

namely syntactics, semantics and pragmatics. *Syntactics* being concerned with language form and symbol combination rules, *semantics* being concerned with how meaning is represented, and *pragmatics*, primary concerned with the function of the language. It is common practice in many different subjects, e.g. data communication, to use a layered model to understand a system of communication. In such a model, the bottom layer is concerned with transmission of physical signals, while the top layer is concerned with the application of the communication. All but the bottom layer rely on the layer below them for appropriate *services*. A semiotic layer in such a layered model of a system of communication would be responsible for semantic representation.

There is no theoretical limit to what might be chosen to be a sign or symbol to represent something else. Therefore, semiotics as a formalised theory may be applied to any discipline and not just those which use recognisable types of language. Because of this more general view, semiotics might be considered to be a useful philosophical foundation for research and pedagogy, since all such subjects are concerned with information, its representation, logic, meaning and function. Indeed, semiotics has a vital role to play in both the theoretical underpinning and practical application of constructivist learning.

Liu and Sun (2002) pointed out that although semiotics and constructivism have different philosophical foundations, they do share a very similar epistemological view. In both, knowledge is constructed through collaboration between participants. Both recognise that meaning will depend on context, and that although the designer of a symbolic representation of information may have had a particular meaning in mind, each participant will develop their own unique interpretation.

Cunningham (1992) considered that signs are used to construct representations of knowledge, but also relationships between those representations. These ideas are particularly relevant to this thesis with its emphasis on the use of semiotic registers to represent information in physics, and *pedagogical relationships* to represent the purposeful relationships between information, exploited for teaching and learning. In physics, as in many other subjects, signs may be imbued with *value* since, according to Cunningham, they "... allow us to compact information into a format that can be referenced in different contexts".

As part of the process of knowledge construction, a learner will invariably be faced with particular signs and symbols. Semiotics and constructivism have similar explanations of the process of understanding the sign or symbol by the learner. Both consider that the learner will use contextually-relevant, prior knowledge to attempt to accommodate the new sign or symbol. This process may be aided by simultaneously presenting the learner with alternative representations, although unless very carefully considered, the teacher's choice of representation may have the opposite effect, confusing the student even further.

As with many other subjects, physics relies on the use of symbols belonging to several different languages, including English, or an alternative human language, mathematics, various types of diagram, etc. At a particular level of abstraction, information is represented through symbols, which in their turn are composed of other symbols, representing information at a lower level of abstraction. For example, a particular circuit diagram might be used to illustrate one of Faraday's experiments. The circuit diagram represents the functional relationships between pieces of electrical apparatus, each of which is represented by a particular symbol. This thesis considers the pedagogical importance of commonly recognisable, composite symbols at a relatively high level of abstraction. It is argued that these so called *semiotic registers* are used by professional physicists, physics teachers and students as tools in the construction of domain-specific knowledge. Also, since *discourse* is recognised as a useful constructivist learning activity, it is further argued that such semiotic registers have a role to play in focusing dialogue between learners during the knowledge construction process.

The constructivist view of learning considers that each individual will construct their own version of conceptual knowledge, even though they share the same symbolic representations of information used by the community of learners. It may be true that acquired concepts are context-sensitive (Lemke, 1994) and that learners do not let go mentally of the various physical representations used to help them construct their knowledge. If this is the case, then particular important representations, the semiotic registers, may take on the cognitive role of key high-level symbols to represent wider domain knowledge. It would follow therefore that focusing on such key representations when teaching might help students in constructing knowledge.

Chapter 8

PHYSICS EDUCATIONAL SOFTWARE

There have always been physics teachers keen to use technology to help support teaching and learning. Likewise, there have always been critics, even amongst fellow science teachers, who would consider the use of technology to be highly problematic. It is debatable whether or not such technological tools, including computer software, have led to measurable pedagogical results, and whether the use has been worthwhile especially set against the expenditure and teachers' time and effort. Of course, the introduction of any type of technology into the classroom is not a panacea for pedagogical problems, and consequently will not turn a poor teacher into a great teacher.

Since the teaching of physics takes place in classrooms and laboratories, the use of computers may have a double pedagogical impact. In a physics laboratory within a modern British secondary school or in a UK undergraduate physics-teaching laboratory, it would not be surprising to find microprocessors being used to monitor and control experiments, or process and log experimental data. Similarly, it is common to find microcomputers running either subject-specific or more general software, in order to help support various learning activities. Word-processing, database, spreadsheet, or graphics software have proven to be useful for physics students when engaged in those various activities which are common to physics and many other subjects, e.g. writing reports, performing calculations, drawing graphs and diagrams. Perhaps the most common subject-specific software to be found would be computer assisted learning (CAL) software, which is designed to teach a particular aspect of the curriculum and perhaps assess what a student has learnt.

Use might also be made of more advanced software that attempts to simulate experiments, systems or phenomena, which, for one reason or another, cannot be reproduced in the simple physics laboratory. Over the last two decades, there is evidence to indicate that using simulation software in physics does have some pedagogical benefits. Various attempts have been made to enrich students' experience through more authentic science using simulation software. However, the use of this type of software is not without problems. In addition to selecting software that is easy for the intended students to use, the physics teacher must carefully consider the educational aims and objectives it offers. As with CAL software, it is important to consider both the subject content, and any implicit or explicit pedagogical approaches the software might take. Attention should also be paid to the prior knowledge required by users, the level of English used, the on-line help available, supporting documentation etc.

No matter how sophisticated simulation software is, such programs cannot replace practical laboratory work. There are some useful programs for simulating complex physical systems that could never be made available in simple laboratories. However, it is highly debatable whether simulations of more common physics experiments, which are able to be performed in the laboratory, should ever be considered. Some physics students find difficulty in relating the practical work they do in the laboratory with the theory that they learned in the classroom. To attempt to solve this important problem, students require adequate learning time and motivation, and the teacher must have a thorough understanding of the nature of experimental science. Many important laboratory skills may be learnt, including design skills (e.g. designing or selecting apparatus), measuring skills (e.g. carefully and accurately using appropriate measuring devices and logging results), mathematical skills (e.g. estimating values, drawing graphs, calculating results from formulae) etc. Even after developing the skills, students may find that their experimental results differ from those predicted by the theory they have learnt, or generated by an oversimplifying simulation software package. This problem of course is an excellent opportunity for the physics teacher to begin to explain about accuracy in measurement, experimental errors, and calculation of results. However, the teacher may have to begin a dialogue with the students concerning a more valid view of the nature of science, and experimentation. Unfortunately, some educational physics sources still seem to perpetuate the naïve view of an experiment: wherein all parameters are maintained constant, except for the two which are allowed to change, the independent and dependent variables. Students should be encouraged to deepen their understanding of science, and not feel to be a failure because their experimental results differ from the textbook. Of course, this may also be a useful opportunity for the pre-service physics teacher to deepen their own understanding of the nature of experiment and its relationship with hypotheses, theories and physical laws.

The use of CAL in physics teaching has had a very chequered history. In the late 1960s and early 1970s there were many physics teachers who created their own bespoke CAL software using various third generation programming languages such as Fortran, Algol and later BASIC and C. Often a great deal of time and effort was expended to produce something which was only applicable to a relative narrow part of the syllabus. It was not surprising therefore, that educational *authorware* packages were introduced to aid in the more rapid development of often poorer quality educational software. Despite pockets of innovation in which the computer user was able to develop software for discovery learning, much CAL software was based upon programmed learning techniques, drawing heavily on the behaviourist learning view of Skinner (1968).

In the 1990s changes in computer hardware, computer software and data communications enabled some interesting new ideas in teaching and learning physics to emerge. Microcomputers became capable of using multimedia data that could be sent between application programs. When preparing a report or presentation, the physics student could be more creative, presenting information as images, audio clips or even video, in addition to the usual text. Because it was relatively simple to network computers together, data could be shared between students across the school or university. The introduction of the Internet meant that students could share ideas using electronic mail or bulletin boards, and search for relevant data on the World Wide Web using various types of search engine software.

Unfortunately, although it is relatively easy to use one of the many Internet search engines to find data, even multimedia data, there is no guarantee that what is received is valid. For this reason and looking ahead to a time when more intelligent, perhaps even mobile, software *foraging agents* will be used to search for relevant data, some development has taken place into meta data standards. The Semantic Web (Hendler, Berners-Lee et al., 2002) initiative has attempted to develop appropriate higher level protocols, based on XML, which could explain to a foraging agent the semantic content of web pages.

The development of CAL software, especially catering for multimedia, is expensive and very time-consuming. When authoring languages were introduced to improve the development of CAL software, it became obvious that the data which represented particular information, and hence declarative knowledge, could be decoupled from instructional software used to deliver it to the student. This was definitely an advantage over earlier, tightly coupled CAL packages, which were difficult to update with new data. Now it began to become feasible to share such represented knowledge. Among others, Tripp (1997) advocated that there was a need for a new methodology which would enable more efficient production of, what was now termed, *courseware*. One approach to the development of a methodology was to consider standards for information representation. Representing information in various forms is clearly a benefit for the majority of students. Therefore any standard for representing knowledge should cater for multimedia data. Obviously, because of the Internet, digitally produced representations of information might be shared between groups of students across the globe.

The recent technological changes in computers and communication systems have enabled newer learning methods to be considered. It is unfortunate that technology is often allowed to lead the development of pedagogy. We tend to consider for what pedagogical end new technology might be used, rather than concentrating on the more important question of what is the nature of the pedagogical problem we wish to solve. That aside, there is evidence of the World Wide Web being successfully used in supporting science education. Batanov and Dimmitt et al. (2002) for example, found that the Internet supported collaborative learning, through enabling school students to communicate with other schools' students, undergraduates, teachers and professors. Through the use of the Internet they were helped with ideas, information, comments and encouragement. Collaborative learning is one of many ways in which students may learn as members of a group, or a "community of learners" as described by Vygotsky (1988) and other constructivists. Relatively recently, several educational research projects have investigated how collaborative learning can be better supported. Suthers and Hundhausen (2001) suggested that this mode of learning required the use of computer-based visualisation tools. In essence visualisation tools are computer programs which illustrate how particular ideas, knowledge, or perhaps concepts are interrelated. The most common type of visualisation tool is the *concept map,* sometimes referred to as a mind map, which uses simple graphical figures, e.g. circles, ellipses, or rectangles, to represent concepts. Relationships between these concepts are represented by lines connecting the geometric figures. In simpler versions of the concept map, concepts and relationships have textual labels. Although such concept maps may be drawn by hand, the software tools for producing them have become quite popular. In more advanced versions of the concept maps, the geometric figure for a particular concept may in turn refer to another map. For illustration purposes, use may be made of colour, images and clip art.

Tony and Barry Buzan (2004) have a reputation for showing how memory and perhaps other study skills may be greatly improved through encouraging students to draw very illustrative concept maps, which they called and trademarked as *mind maps*. There have been sporadic research results which indicated that these tools, whether created by computer software or not, do help students to organise their ideas, brainstorm and interact with their peers. Van Bruggen, Kirschner et al (2002) found in their research that concept mapping led to more intensive dialogue between learners. Chiu (2002) concluded that the use of concept maps reduced the cognitive load of learners.

In addition to these more general concept map programs, there are examples of visualisation tools which concentrate on a particular subject domain. Technically these tools are like the freer versions of concept maps, but with pre-structured visual representations. Cole and Wersht (1996) found that these tools posed constraints on some students, preventing them from expressing their thoughts. Although on the whole there is evidence to show the usefulness of these visualisation tools in various learning contexts, it is clear that more research is required into their use with larger groups of learners perhaps sharing diagrams across the Internet.

Jonassen (1994) used the term *digital artefact* to describe technological tools used within a learning environment. The term artefact being taken from work by Wartovsky (1979) and colleagues writing on socio-cultural theory. Such artefacts are also mentioned in work by Vygotsky (1987) and other constructivists when considering the development of understanding by a learning group mediated through symbols. Concept maps may be considered both as material objects and, in more abstract terms, as symbol systems. Visualisation tools are not necessarily unbiased, and the representations of knowledge that they help produce are not the passive end product of knowledge elicitation. They are instead a means of conflict and negotiation within the learners' social group.

To sum up, there are many different types of computer software which may have pedagogical use. Concept maps are useful visualisation tools when used with some students and pre-service teachers, especially when sharing ideas and investigating how those ideas interrelate. CAL software still has a role to play in teaching and learning, although many authors consider that such software should be based upon appropriate learning methods rather than more behaviourist, pedestrian, programmed learning techniques. The World Wide Web is a vast potential source of information for students. However, since there is no guarantee of the validity or quality of the information which is returned by search engines, the teacher has an important role in guiding students to appropriate, context related information. The development of *portals* by teachers and interest groups is a possible way of giving students context-important information as well as paths to more relevant data. Some students have been encouraged to build their own subject related web sites; although this clearly requires time and effort on behalf of teacher and students. It could mean also that the students' focus of attention has moved from a particular science subject towards Internet technology.

There are of course many different factors on which to base a comparison between these software tools. Each has its own strengths and weaknesses. All of them may be used within a learning environment and may be required to interface in some way with other learning mechanisms. They all represent in some way certain aspects of human knowledge. Therefore they could be considered as complex channels of data, hence related information, enabling the student either to investigate the software designer's knowledge encapsulated in the program, or alternatively to create a representation of their own knowledge. The roles of the designer and learner, enabled or restricted by the software, may be considered as a measure of how well a particular software tool may contribute to a particular constructivist learning environment. The role of the designer is primarily concerned with representing some aspect of knowledge, and hence there must be appropriate relationships between the represented, constructed knowledge and pre-existing concepts. The role of the learner is perhaps more complex, but may enable an amount of personalisation of the knowledge investigated or constructed. Although the various software tools differ in the freedom of the use that they give to both the designer and the learner, when they are used in a constructivist learning environment they are all broadly based on the notion that the informational content and the process of interacting with it influence the knowledge constructed by the student end user.

Attempting to model even simplified human knowledge[2] has been a major research topic in both artificial intelligence and cognitive psychology. In the latter, attempting to develop feasible mental models has led some researchers, notably David Merrill, to consider the modelling of knowledge in instructional systems. A common mental model used within aspects of cognitive psychology consists of knowledge structures or *schemas* and processes for using these or *mental operations*. Merrill (2000), argued that through careful analysis of subject matter, useful external representations of knowledge will emerge for instructional design and understanding of internal representations, i.e. conceptual knowledge structures, of the learner. Several similar approaches have also been seen. These have led to the decoupling of modelling knowledge for learning from design of the mechanism which will present this knowledge to the learner. Considering how to model knowledge for delivery by a variety of different instructional systems has led towards the development of so-called *learning objects* or *knowledge objects*.

Research is still continuing into the desirable attributes and structure of so-called learning objects. Such a term is being used reasonably freely to describe a unit of shareable, represented information. Many consider that a learning or knowledge object should focus

[2] If human knowledge is considered to be basically subdivided into procedural and declarative elements, some subject domains may use the simpler term *information* instead of declarative knowledge. At a very simplified level declarative knowledge may be considered in terms of interrelated atoms; where the interrelationship is conditional, we have a rule, where unconditional, we have a more simple predicate. On the other hand procedural knowledge refers to the logic of how such knowledge is to be manipulated or processed.

on one particular topic and have defined prerequisite knowledge and in turn deliver specific outcomes. However, despite some co-operation between research groups there is still some disagreement regarding the nature of the *granularity* of the information represented, and the precise nature of a topic. In this thesis the term learning object has been chosen to indicate information on a particular topic in physics. Each learning object is fabricated from a sequence of information *frames*, but it is left to the physics teacher to consider the number of such linked frames and therefore the granularity of information in a taught topic.

Chapter 9

MODELLING PEDAGOGICAL RELATIONSHIPS

Effective teachers are required to make complex pedagogical decisions in the classroom, in order to provide possible routes for their students to acquire understanding of concepts. Subject teachers must acquire appropriate and sufficient content knowledge, general pedagogical knowledge and PCK, in order to fulfil their vital role in education. However, there are many factors which will affect the pedagogical process, not all of which are under the teacher's direct control. The effective teacher may enhance and adapt their PCK in response to some of these uncontrollable changes. Of course, as with other human knowledge, PCK is complex. But, despite this complexity, there are aspects of PCK which may be modelled as either declarative knowledge, procedural knowledge or possibly a rapprochement of the two. Deciding on which of these models is more appropriate will depend upon whether we wish to stress the epistemology as *knowing that* or *knowing how* (Winograd, 1975).

A pre-service teacher may be able to acquire some foundational PCK concepts through a teacher education course. Serving teachers may also be able to pick up ideas on new ways of delivering part of a syllabus through occasional, in-service training days. However, teachers will acquire and modify most of their tacit knowledge through the day-to-day process of teaching. The working teacher will acquire useful teaching skills which must be underpinned by a similarly acquired conceptual knowledge base.

The professional physicist and physics teacher both develop their own, personalised conceptual knowledge base. But unlike the professional physicist, the teacher must structure their knowledge base not just for their own understanding, but for that of their students. Being able to teach students possessing a wide range of abilities and foundational knowledge, an effective teacher must have PCK which is rich in the use of descriptive models, pedagogical methods and relationships. Of course, the effective teacher must develop a learning environment in which all types of student may acquire their own concepts. The teacher's PCK will influence how they design activities, as well as how they represent the taught subject. Mizoguchi and Kitimura (2001) found that teachers' subject knowledge influenced the way they represent that subject to their students. Since the effective must use of wide range of different representations to cater for the different types of student, it follows that the effective teacher must have a rich understanding of the taught subject. Without sufficient care, a particular way of representing a concept, instead of being an aid to the student's understanding, becomes a hindrance.

Identifying and describing the relationships between concepts, may be unimportant in some contexts. However, to help someone learn or teach, it is vital. In a constructivist learning environment, considering conceptual relationships is perhaps an implicit task performed by the community of learners. However, understanding the nature of the knowledge construction process will require relationships between concepts to become explicit, and therefore there is a requirement for visualising them. This thesis considers that such identification and visualisation of relationships between an experienced teacher's knowledge may help to support pre-service physics teachers in their knowledge co-construction tasks. Because of the visualisation capabilities of modern computer systems, it is a logical step to consider their role in this endeavour. Therefore there is a perception that what is required is a tool for creating a representation of the teachers', or for that matter the students', conceptual knowledge. In this context of constructivist learning, the computer is considered as a digital artefact having a semiotic role in enabling mediation through symbols and signs.

The previous chapter described briefly the most common types of computer software that are used to help in the teaching and learning of physics. Each of these types may have a role to play in enabling pre-service physics teachers to investigate their conceptual knowledge, as well is that of a more experienced teacher. Concept maps for example would enable the creation of a diagram representing a very high-level abstraction of how concepts interrelate. But such software is not concerned with how such concepts may be represented in terms of pedagogical or subject knowledge. CAL software has a role to play in teaching or assessing some aspect of the syllabus. But such software seldom enables the student to investigate the stored knowledge and discover possible relationships. There does not appear to be software specifically for pre-service teachers. The knowledge representation features of knowledge-based software would clearly be of use, but such software is usually concerned with processing stored facts and rules by one or more inference algorithms.

Therefore it was necessary to design prototype software which would enable a user to construct or investigate relationships between represented domain-specific knowledge. Such knowledge and its interrelationships would then be used to aid in the understanding of concepts. Instead of representing a concept as a simple geometric figure, as is the case with concept maps, knowledge for concept acquisition was to be represented as a *learning object*. In its turn, a learning object was to consist of a sequence of *knowledge frames* or simply *frames*. Each frame was to be based upon a particular type of common *semiotic register;* either one familiar to the physicist, or one common to the physics teacher and learner. Finally, any frame, or any localised area in a frame, termed a *hot spot,* may be related to any other frame. The software was given the acronym KEPLER, representing "Knowledge Environment for Physics Learning and Evaluation of Relationships".

The aim of this research was not just to design a model of domain-specific knowledge (e.g. a topic in physics), but to include in that model an aspect of the physics teachers' PCK. Then to consider how such a model might be represented in computer software. Of course, designing any knowledge model may begin by deciding on which design or knowledge representation paradigm to choose. The symbolist (knowledge-based) paradigm was chosen, rather than the connectionist (neural network) one, because the model was to focus on attempting to make relationships explicit. Therefore, again stressing the explicit relationship aspect, it followed that there might be a bias towards the design a declarative knowledge structure compared with a procedural knowledge one.

Over the last few years many research groups have been considering how subject knowledge might be shared over the World Wide Web. In contrast to the earlier, more context-free ways of representing knowledge in artificial intelligence (AI), such as predicate logic, rule sets and frames, a new approach was towards the development of an appropriate *ontology*. Gruber (1993) borrowing the word from the study of philosophy, defined an ontology as a *specification of a conceptualization*. By this he meant a formal description or specification of the various concepts and relationships which exist in a particular domain or context, for an agent, or community of agents. Although ontologies have been developed for a range of different subjects, there does not appear to be an appropriate one which considers physics knowledge as its source. Following an analysis of the type of information which is presented to students in physics textbooks, as well as numerous conversations with physics teachers, the following possible, high-level abstraction emerges. Figure 1 shows a possible model for the development of an ontology for physics terminology.

This high-level abstraction serves to illustrate the complex nature of what physics means to physicists. It also reveals that when attempting to define even a high-level abstraction we must consider both the semantics of language and our more general world view. What begins to emerge is the taxonomic classification of *objects*, and the *relationships* between these objects and *actions* performed by *agents*. When categorising the different objects or entities with which physics is concerned, we must include reference to *physical things*, such as apparatus and physicists, objects that have both a physical and semiotic nature, such as equations, and entities that are mental constructs, such as concepts. When considering how to categorise *agents*, the active entities within an experiment, we must include both human and nonhuman.

Category	Description
Action	Something performed by a human or agent.
Phenomenon	Something observed.
Object	An identified physical thing. An identified mental construct.
Event	Something happening at a place and time.
Function	An identified behaviour by an object.
Attribute	A property of an object.
Relation	Association in some form between objects, attributes, functions, etc.
Agent	That object which performs an action.

Figure 1: An example of a high-level ontology for physics knowledge

When attempting to consider the design of a high-level abstraction of physics pedagogy, the task proves to be impossible because of the complexity of the subject and, as indicated in previous chapters, the abstraction becomes recursive. The recursive nature of such an abstraction of physics pedagogy is due to physics, the teacher's view of physics, the teacher's view of pedagogy are all understood in and through abstractions.

Nevertheless, it is possible to use the high-level abstraction for the subject of physics, or an ontology of physics terminology based on it, to analyse a lecture, textbook chapter, or other source of content knowledge. Since, by their very nature, physics lectures and textbooks are concerned with the *learning* of physics concepts, the analysis may include the use of concepts and terminology which the professional physicist might not have to use, but are essential PCK. What emerges is the physics teachers reliance on a wealth of different words or phrases to represent *actions* and *relationships*. As mentioned in an earlier chapter, it is a matter of concern that the acquisition of concepts may require information to be presented to students in various semiotic forms, and the social interaction between a group of learners and this multimedia information is pedagogically significant. Relying solely on spoken, or perhaps written language, may delay the acquisition of concepts or even enable the acquisition of incorrect concepts. In a classroom situation the teacher may receive instantaneous information back from students, which may be used as evidence of understanding. Such a teacher is able to use various media to reinforce partially understood ideas, or attempt to remedy misconceptions. Clearly, if the teacher is physically absent, as in the case of distance learning, the intercommunication between teacher and student becomes qualitatively poorer.

Fortunately or unfortunately, physics is not taught in isolation. Physics students are not apprentices learning *on-the-job*. Physics is taught in and through a societal framework involving group interaction, conventions of status and behaviour, pedagogical targets, parental and student expectation and so on. Although the physics teacher in the UK may make use of different ways of representing information for students, written and spoken English is invariably dominant. Therefore, we rely on the teacher's power of description, including the appropriate choice of phrases relevant to the context. Therefore it is not surprising that we are faced not just with questions concerning the linguistic-pedagogical skills of the teacher, but with the fundamental question regarding the very role of language in science.

Ford and Peat (1988) concluded that a particular scientific worldview is *enfolded* within the ways scientists use language, and that insensitive use of language can lead to blocks in scientific creativity. Of course, every physics lesson is also a language lesson. It has been shown by Medin and Ortony (1989) and others that many science students have difficulty in recognising verbal clues in problem descriptions. It has to be efficacious for pre-service physics teachers to have the opportunity to consider their views on the nature of science, and of their role as science teachers. Likewise, there should be means by which they can reflect on how they see the subject physics, and how their conceptual understanding is communicated to their students through the medium of language in the widest sense of the word.

Many physicists have postulated that language does not just have a passive role in science. It does much more than merely convey information; it plays an active part in the development of concepts. David Bohm considered that the language used in physics has helped to form the majority philosophical view that the physical universe is best described in terms of things rather than of processes. To some physicists, nouns are therefore much more important than verbs. A noun-oriented abstraction leads us towards considering stability of a physical system, which may be described in terms of static attributes. Describing the physical world *in flux*, to use an old-fashioned physics term, does require more use of verbs, and incidentally will require more data if the communication process was to be analysed using information theory. Usually a static description will suffice if we are considering macro phenomena[3]. Physics has begun to uncover that the subatomic, nuclear or quantum world is anything but static. The cosmic world of stars, galaxies and black holes is similarly extremely dynamic. However, read any physics textbooks or listen to any physics lecture, and one very soon realises that to understand physics requires understanding a vast number of different relationships between things.

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[3] The term ***macro*** here relates to physical objects of a similar order of size to human being. The terms *micro* and *super macro* would correspond to phenomena at some atomic/nuclear level and cosmic level respectively.

It is quite interesting, although not always rewarding, to discuss with science students whether they have really signed up to the basic tenet of science, and therefore of physics; namely the principle of cause and effect. Unfortunately, students are exposed to many views of the world which are definitely at odds with this principle. However, the relationship between causes and corresponding effects is ***the*** relationship which underpins all of physics. To infer that a particular causal relationship is telling us something about the way the physical universe is behaving, we must seriously consider the repeatability of any test of it. That is we must begin to consider designing experiments. Although the interest in cause-and-effect begins with an observation of some phenomenon, the discipline of physics requires us to identify causal relationships, which have qualitative and quantitative attributes.

In the simplified, high-level abstraction of physics knowledge (Figure 1), components such as actions, objects, and events are all interrelated. However, it becomes clear that many of semiotic registers used by the physicist, which would be included in the category *object* have relational characteristics themselves. Consider for example three commonly used semiotic registers; a table of results, a Cartesian graph and an equation or formula. Each of them, in their own way, represents a relationship between two quantifiable or measurable parameters. A table of results may represent the state of certain discrete, quantitatively measured parameters, at various stages in an experiment. It may be necessary for the scientist to use the table to interpolate intermediate parameter values assuming that the relationship is continuous. A Cartesian graph is a symbolic representation of a relationship between two parameters when measured over a particular range. Displacement is used to represent particular values of the parameter. An equation or formula is a symbolic representation of an overview of the relationship between the potentially quantifiable parameters.

As we delve deeper into the semiotic nature of the artefacts which are used in physics we discover further relationships. A circuit diagram for example is a stylised representation of how electrical apparatus is connected, or more succinctly, it is a representation of how electrical apparatus is interrelated, not in normal space but in a theoretical electrical space, where what is important is *how things are connected together* and not *where things are*. In more complex cases still we are faced with perhaps considering the relational nature of hypotheses, theories and physical laws.

An experienced physics teacher's PCK will involve a wealth of different types of relationship between objects, agents, and events etc. Unfortunately, ways of expressing relationships are standardised only when such relationships are mathematical or Boolean logical. Therefore, when we investigate how these relationships are described in physics textbooks, lectures and other sources, there are subtle differences in how they are expressed. Nevertheless, it is possible to identify at least some of the major categories of relationships used by physicists and physics teachers. It is also possible to identify various types of uncertainty and negation which may be applied to a particular relationship.

Over a four-week period analysis was made of similar chapters from a representative set of Advanced Level and first-year undergraduate level physics textbooks. Figure 2 below shows a selection of the phrases which were identified as representing common types of relationship as used in physics. Not wishing to force the different phrases into a predefined declarative model, the categories into which the phrases have been placed are basically shorthand descriptors. The exact meaning of each phrase will often depend upon the context in which it is used. Indeed, changing the context may result in the phrase having to be moved to a different category.

Because an earlier chapter has considered the importance and complexity of using analogues and metaphors in teaching physics, phrases representing similarity in its various forms have not been considered here.

Possible category	**Examples**
Boolean logical	equal to, greater than, greater than or equal to, less than,less than or equal to, not equal to, never the same as, mathematically identical to
Boolean logical + level of uncertainty	almost the same as, almost equal to, almost identical to, considered to be the same as, almost always is equal to, of the order of, approximately equal to , can be approximated to, assumed to be, estimated as, tends towards, very much greater than, very much less than, in the range, equal and opposite to, complementary to, opposite to, almost opposite to
Calculated result	sum of, product of, calculated from
Scientist role	discovered by, discoverer of, discovered through, discovered from, invented by, inventor of, proposed by
Property	property of, possessed by
Part of	fundamental part of, component of, horizontal component of, vertical component of, part of, contains, consists of
Behaviour of	force between, attraction between, repulsion between
Causal	depends upon, mutually dependent upon, a consequence of, a cause of, independent of , affected by, caused by, related to, based upon, leading to, will yield
Quantitative/qualitative dependence	increases as, decreases as, diminishes as, inversely proportional to, proportional to, increases linearly with, decreases linearly with, increases exponentially with, decreases exponentially with, related to, diminishes as
Types of model	a model of, acts as, can stand for, can be thought of as, can be considered to be, can be replaced by, symbol representing, replaced by, replaced with, can be used to describe, can be used to explain, something like, the principle behind
Purely pedagogical	a way to remember, short-hand for, mnemonic for, can be remembered by, may be thought of as
Spatial + static	parallel to, inclined to, connected to
Spatial + dynamic	accelerates towards, accelerates away from, rotated about, passing through, directed towards
Temporal	periodic, rate of change, changes with time
Class based	belonging to the same class as, in the same category as, type of
Defined or derived	inferred as, inferred to be, derived from, defined as, is by definition
Illustrative	example of, worked example of, illustration of, can be used to describe, described by, demonstrates that
Physics + units of measurement	measured in, converted into
Physics + measuring apparatus	measured by, measured using

Figure 2: Categorical overview of relationship-like phrases

Classifying the phrases which represent relationships in physics pedagogy is a complex philological task. However, what does emerge from a consideration of the phrases, is a possible set of rules involving certain broad categories.

Rule 1: A particular phrase may belong to one or more of the following categories: mathematical, logical, causal, spatial, temporal, taxonomic, metonymic, purposeful, procedural, …

Rule 2: A particular phrase may involve an implicit or explicit metric or comparator.

Rules 3: Where a particular phrase does involve an implicit or explicit metric or comparator, then may be evidence of a particular type of uncertainty.

Rule 4: A particular phrase may make use of Boolean logical operators.

There are two important observations which emerge from this exercise. These observations have important consequences if the various relationships in physics are to be expressed in language alone. Firstly, there are many different ways to express a particular relationship. This can be seen through considering some of the examples in Figure 2. Secondly, slight changes of words in a phrase may radically alter its meaning. For example, consider the difference in meaning between the following similar phrases. Unfortunately each phrase may also have multiple meanings when prefixing different object phrases:

"measured by"	e.g. "measured by John", "measured by means of a voltmeter"
"measured in"	e.g. "measured in metres", "measured in 2 different ways"
"measured with"	e.g. "measured with care", "measured with a rule"
" measured at"	e.g. "measured at boiling point", "measured at the North Pole"

These problems may be difficult to overcome especially in learning situations where the students do not have advanced linguistic skills. Obviously, if the physics teacher makes use of other media, including the various semiotic registers already considered, such as diagrams and graphs, understanding the relationships may be reinforced. However, this does perhaps highlight an important consideration when developing learning material for distance learning courses. The absence of a teacher, trained to spot when a student fails to understand something, and therefore presents a new alternative, explanatory view, means relying on interactive, cross referenced, multimedia data; a very poor substitute for a teacher's skills.

All of the relationships considered in this chapter, as well as those based on analogues and metaphors, are vitally important to the work of the physics teacher. The effective, experienced physics teacher will have refined their mechanism for selecting particular ways of expressing relationships in a given context. Through practice they will have learnt which phrases to avoid, which phrases may need alternative reinforcement, and which phrases contain useful links back to previously taught topics. In this thesis the term *pedagogical relationship* is defined as any relationship exploited for the purpose of helping learning to take place. Such a concept is here considered to be an essential component of the physics teacher's PCK. Therefore one of the major aims of KEPLER is to enable such relationships to be investigated by novice physics teachers.

Chapter 10

KEPLER

KEPLER ("**K**nowledge **E**nvironment for **P**hysics **L**earning and **E**valuation of **R**elationships") is a prototype software tool, created as part of this research, which enables a user to develop a series of *learning objects*; each learning object being composed of a sequence of *frames*. Each frame is based on a typical *semiotic register* for the application domain. Each semiotic register, or a localised area on it (termed a *hotspot*), may be explicitly related to another semiotic register or hot spot. Each explicit relationship contains information primarily concerning the reason for the relationship. Although any taught subject which makes use of particular, recognisable semiotic registers might have been chosen, physics was considered as being appropriate, firstly because of the problems related to the training of pre-service teachers, and secondly because it is rich in both semiotic registers as in relationships between content knowledge (CK) and pedagogical content knowledge (PCK).

The designed learning objects, containing frames, may be investigated by another user in a number of ways. KEPLER is able to display each frame within a learning object in much the same way as other types of CAL software. However, a user is also able to investigate the relationships between frames or their hotspots. All navigation is achieved using the mouse. As the mouse moves over a semiotic register the availability of relationships with other frames changes. A localised area or hotspot, which represents a semantically rich part of a semiotic register, may be made visible or left to be discovered by the user. The right mouse button enables different menus of options to appear, depending on the mouse's position.

Although KEPLER may be used as traditional CAL software, its primary purpose was to be used to investigate the purposeful pedagogical relationships between represented knowledge. Therefore, the initial user might be considered to be an experienced physics teacher who uses KEPLER to create a representation of some declarative knowledge they have about a particular subject. In addition to representing a sequence of frames within a learning object, the experienced physics teacher may encapsulate answers to why certain knowledge is conceptually and/or pedagogically related. The second user, or group of users, might be considered to be pre-service physics teachers, who may use KEPLER to investigate the representation of the experienced physics teacher's pedagogically related knowledge of a physics topic.

The term learning object was chosen as appropriate to this research and not to rival any emerging definition from the E.-learning community. Amongst educational researchers and commercial enterprises concerned with the delivery of information for learning via the Internet, the term learning object has been used to describe almost any digital resource that can be used to support learning. For several years now there has been debate concerning what is defined to be a learning object, the structure of knowledge it represents, its level of knowledge granularity and its reusability. Possibly the most successful model is that suggested in the work of Merrill (2000), where the learning object is considered as independent of the instructional system which presents such encapsulated knowledge to the learner. Much of the development of instructional systems are based around ideas of learning due to the behaviourist Gagné (1977).

Where KEPLER differs from instructional systems as envisaged by Merill and others, is that it focuses on the nature of *pedagogical relationships* between knowledge. This emphasis on the primacy of relationships goes beyond those relationships within instructional systems. In instructional systems the relationships between the various knowledge elements are of predefined and relatively simple types. The first type of relationship is basically the accepted epistemological view of the knowledge elements making up the knowledge structure. For example, those relationships which are concerned with the classification and categorisation of the knowledge. The second type of relationship is more related to the instructional view of the knowledge elements. For example, one knowledge element is a learning prerequisite of another. The first relationship (epistemological) might be viewed by some as a relationship which is inherent to the knowledge under scrutiny. Hence, for example, two elements are related because they belong to the same class. However with the background of a constructivist learning paradigm this relationship may vary with the individual's view of the knowledge. Implicit in the second relationship (instructional) is a value judgement identifying that one piece of knowledge is definitely a prerequisite for the acquisition of another. It appears that including this latter type of relationship may prevent the knowledge structure from being totally independent of the instructional system which presents corresponding data to the learners.

KEPLER was designed to help promote discussion on the pedagogical importance of relating knowledge together to help students acquire concepts. It is recognised that each student, or each pre-service physics teacher, will acquire their own version of conceptual knowledge. Therefore, each will develop their own internal conceptual structures and inter-conceptual relationships. It is also recognised that there are different sources for inter-conceptual relationships, and that all of them may be employed in personalised concept acquisition. In particular, there may be inter-conceptual relationships which are shared amongst the physics community, that is agreed current knowledge. There may also be very personalised inter-conceptual relationships which represent some tacit, pedagogical knowledge acquired by an experienced physics teacher over a considerable period of time. It is also important to state that KEPLER, like any other knowledge-based software tool, delivers data and shows relationships between data. Therefore, of course, it relies on the user to interpret data as meaningful information, and relationships as possible conditional or unconditional declarative knowledge.

It had been thought that, because of the claim by software engineers that *object orientation* (OO) enabled more *real world* modelling, KEPLER would be developed using OO. However, it was found that even modern OO software fell short of expectations, primarily in its inability to be able to create classes at run time, instead of just at design time. It was also considered to be inappropriate because of the lack of partial or fuzzy inheritance. It was also considered to be appropriate to test the ideas behind KEPLER to developing a prototype system using the most commonly available, inexpensive software.

KEPLER was designed to be used on a stand-alone microcomputer running under the Microsoft Windows operating system (95, 98, 2000, ME or XP). Various programs were considered for its development, finally it was decided that the software most commonly found in secondary physics schools and university physics departments would be used. Microsoft Visual Basic 6 was chosen for developing the user interface and Microsoft Access 97 for developing a relational database holding data and images which contained in the frames, learning objects, hotspots and pedagogical relationships.

The unit of knowledge on which KEPLER is based is called a *frame* and consists of:

- the frame's title (text)
- an image (based on a JPG, BMP or WMF file)
- a short description of the image (text)
- a paragraph of explanatory text
- a list of key words categorising the contents of the frame.

Although the prototype software is based on this frame structure it could readily be changed to incorporate different media including audio and video. The image within a frame may represent any information, but for this research it is considered as any common semiotic register in physics or in physics pedagogy.

For example:

In physics: a graph, equation, exemplar, definition, unit of measurement, hypothesis, proof, formula, diagram, apparatus etc.

In pedagogy: a question, answer, worked example, explanation, illustration, summary, counter example, clue, etc.

A localised part of an image within a frame is termed a *hotspot*. Any number of hotspots may be designed for an image. The hotspot is made active through the frame belonging to a particular learning object. Each hotspot is given a description.

A *learning object* consists of a sequence of frames. Frames however may be re-used in any learning object. Each learning object has a textual description and a set of keywords describing its content and purpose.

One or more *pedagogical relationships* may be defined between:

- two frames
- a hotspot in one frame and another frame.

Each pedagogical relationship belongs to a particular *type*. New *types* may be defined. Each pedagogical relationship will have an explanatory paragraph of text describing its purpose. The various defined items (frames, learning objects, hotspots, pedagogical relationships) may be created, edited or deleted.

Using KEPLER to create or edit learning objects and frames obviously required the use of keyboard and mouse. However, the prototype was designed to enable the end-user to interact with the displayed information and investigate the knowledge and relationships through use of the mouse alone. Therefore, since the image in a frame might contain hotspots it was necessary for the software to be able to display different user options as the mouse was moved.

KEPLER is designed for representing a PCK structure for physics, although it could be used for other subjects which rely on diagrams and other semiotic registers. It could be argued that, as in the case of concept maps (Cañas and Carvalho, 2004), the learning objects, knowledge frames and pedagogical relationships do not constitute a knowledge representation scheme. Hence they are not able to be translated into a formal representation for inference or other AI techniques. However, this is not the case since at least a semi-formalised version of the declarative knowledge elements was designed. Figure 3 shows a description of the related knowledge in Backus Naur Form (BNF) (Naur, 1960).

Frames
< frame > ::=
< pedagogical_semiotic_register > < title > < description > <keyword_list>

Learning Objects
< learning_object > ::=
<learning_object_ frame_list > <title><keyword_list>
<learning_object_ frame_list > ::=
<linked_frame>|<learning_object_ frame_list >
<linked_frame> ::= <backward_pointer><frame><forward_pointer>

Pedagogical Relationships
< pedagogical_pipe > ::= < pedagogical_relationship > | < pedagogical_pipe >
< pedagogical_relationship >
< pedagogical_relationship > ::=
< relationship_type > < pedagogical_purpose > < description > < route >
< route > ::= < starting_position > < direction > < ending_position >
< starting_position > ::= < position >
< ending_position > ::= < position >
< position > ::= < learning_object (l) > < frame (l, j) > [< hot_spot (l,j,k) >]
<hot_spot(l,j,k)> ::= <radius><x-centre><y-centre>
< pedagogical_route > ::= < starting_point >

Key words
<keyword_list> ::= <keyword>|<keyword_list><keyword>

Figure 3: Backus Naur Form (BNF) for KEPLER's declarative knowledge syntax

Using relational modelling techniques the BNF description became the basis of a normalised relational database. Figures 4 and 5 show the corresponding Entity Relationship Diagram and rationale for the various tables. The relations represented frames, learning objects and pedagogical relationships. The learning object relation contains a reference to the particular starting frame. The route through the knowledge frames for a particular learning object is represented in a separate relation, thus enabling frames to be reused. Pedagogical relationships, including those associated with hotspots in a frame's image, are not *hardwired* into a frame's relation that associated with how the frame is used, in the context of a particular learning object. Hotspots, the localised areas in a frame's image considered to be important in the context of a learning object, are represented by circles. Therefore, the corresponding relation requires three numeric values; representing centre coordinates and radius of the circle.

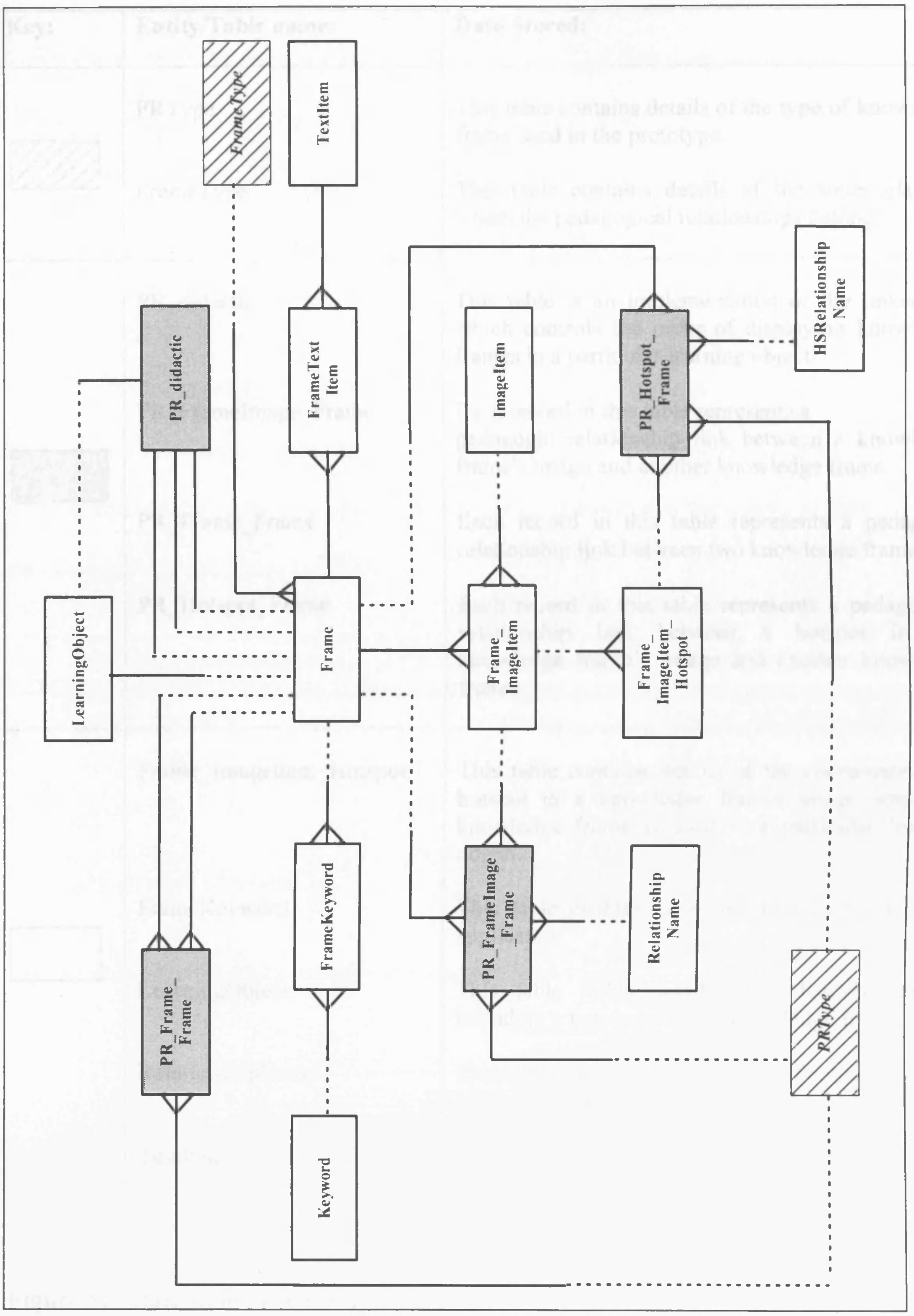

Figure 4: Entity Relationship model of KEPLER's Relational Database.

Key:	Entity/Table name:	Data Stored:
	PRType	This table contains details of the type of knowledge frame used in the prototype.
	FrameType	This table contains details of the super class to which the pedagogical relationships belong.
	PR_didactic	This table is an implementation of the linked list which controls the order of displaying knowledge frames in a particular learning object.
	PR_FrameImage_Frame	Each record in this table represents a pedagogic relationship link between a knowledge frame's image and another knowledge frame.
	PR_Frame_Frame	Each record in this table represents a pedagogic relationship link between two knowledge frames.
	PR_Hotspot_Frame	Each record in this table represents a pedagogical relationship link between a hotspot in and knowledge frame's image and another knowledge frame.
	Frame_ImageItem_Hotspot	This table contains details of the coordinates of a hotspot in a knowledge frames image when the knowledge frame is used in a particular learning object.
	FrameKeyword	This table enables keywords to be reused in the application.
	LearningObject	This table holds details of a learning object, including a link to its initial knowledge frame.
	RelationshipName	This table holds an updatable list of commonly used pedagogical relationships.
	TextItem	This table holds a textual descriptions used in the various knowledge frames.

Figure 5: Rationale for entities and relations

KEPLER attempts to cater for two classes of user. The first user, the *modeller*, uses the software tool to create a representation of knowledge concerned with a teacher's view of a particular aspect of physics[4]. The second group of users, the *investigators*, use the software tool to investigate the interrelationships between information within frames.

KEPLER represents knowledge in a hierarchy of three levels. As illustrated in Figure 6 below, it is envisaged that each level of knowledge corresponds to a particular type of teacher's knowledge. A useful metaphor to illustrate the relationships between the various knowledge types is as shown below with, together with the source of that knowledge for a particular teacher.

KEPLER knowledge type	Knowledge source	Corresponding metaphor
knowledge base	overall concept	crystal (ordered solid)
learning object	PK	molecule
knowledge frame	CK	atom
hotspot and pedagogical relationship	PCK	chemical bond

Figure 6: Knowledge types and corresponding sources

[4] Although KEPLER was designed to enable the creation and investigation of the PCK of a physics teacher, it could in fact be used for any taught subject which makes use of interrelated information.

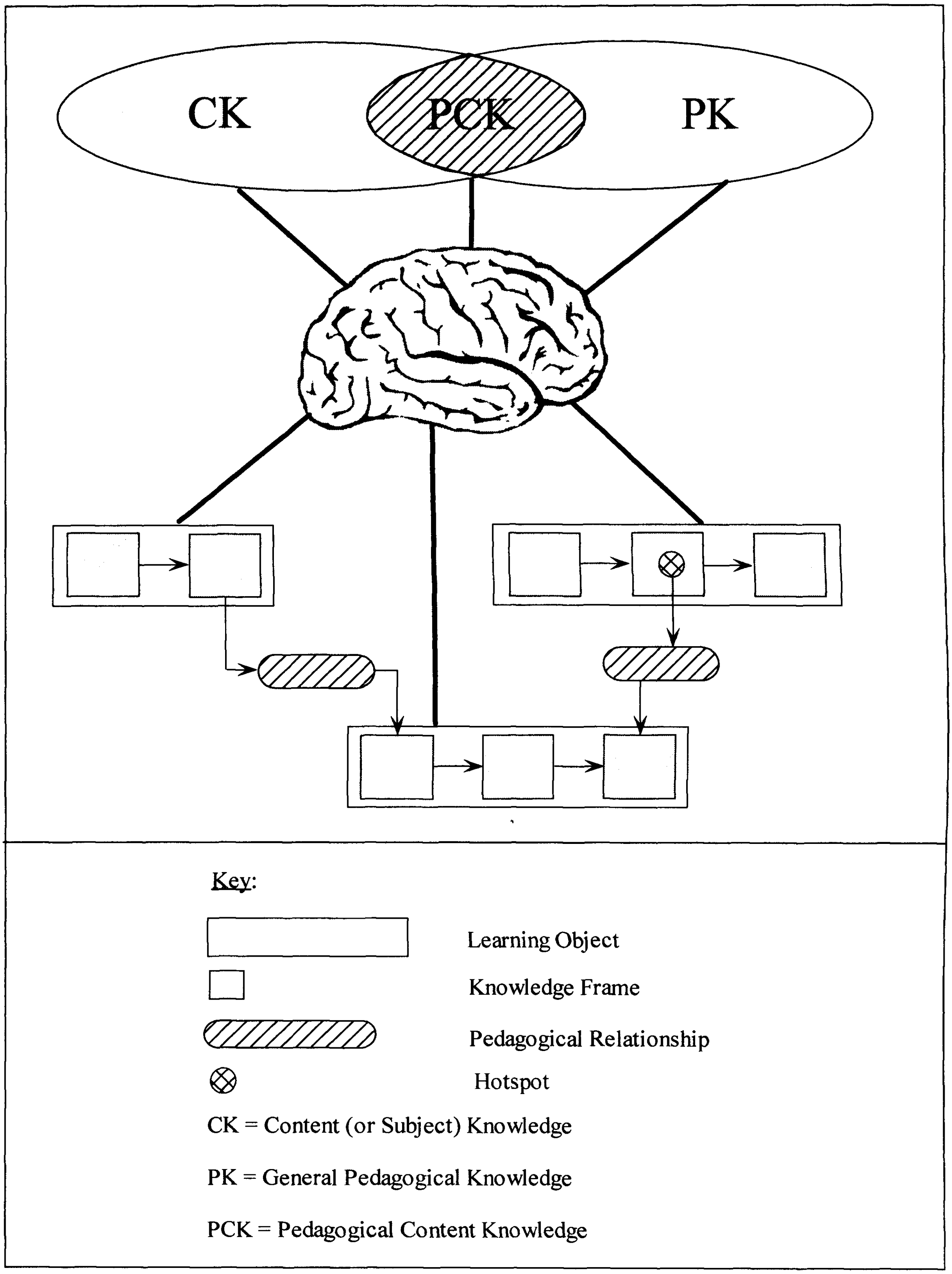

Figure 7: Relationship between the teacher's knowledge and KEPLER

Although KEPLER does not restrict how the modeller sets about designing knowledge to represent a concept, it may be useful to follow a particular methodology similar to the one below:

1. Select a topic and identify the learning objectives.

2. Draw a simple concept map showing the relationships between identified concepts.

3. Outline bullet points for possible learning objects for the chosen interconnected concepts.

4. Investigate existing learning objects in KEPLER.

5. Investigate existing reusable knowledge frames in KEPLER.

6. Investigate other sources of information.

7. Analyse information sources, identifying possible semiotic registers and major relationships.

8. Search for appropriate images and diagrams etc.

9. Check the copyright of source material.

10. Create any other diagrams using appropriate simple graphics software. Save diagrams in an appropriate image file.

11. Create learning object shells using KEPLER.

12. Edit existing reusable knowledge frames using KEPLER.

13. Edit learning objects using KEPLER. Identifying the sequence of the knowledge frames.

14. Identify and check keywords for learning objects and knowledge frames.

15. Use KEPLER to test the basic navigation through each learning object.

16. Edit learning objects and/or knowledge frames when necessary.

17. Identify relationships between frames or image hotspots.

18. Use KEPLER to create pedagogical relationships.

19. Test learning objects, frames and relationships using KEPLER.

In order to create or edit a learning object, frame, hotspot, and pedagogical relationship between frames or hotspots, KEPLER presents the following dialogue to the modeller.

KEPLER class of user: *Modeller*

- The user begins by selecting the task from the maintenance drop-down menu.

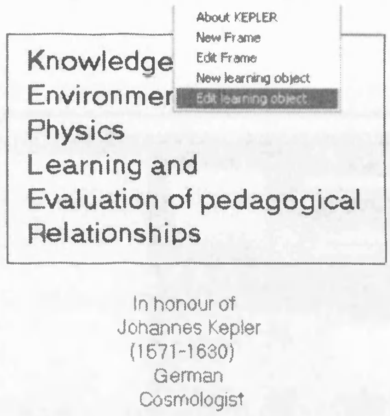

Figure 8: Selecting a maintenance task.

- Searching for existing knowledge frames using keywords, or by picking the frame from a drop-down list.

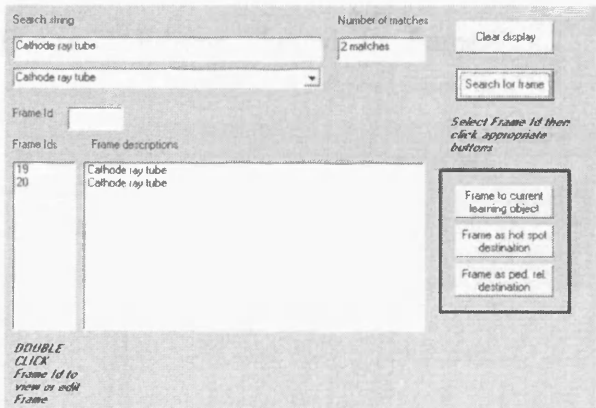

Figure 9: Searching for a knowledge frame.

- Creating a new knowledge frame begins with selecting an appropriate image file which will correspond to a particular semiotic register.

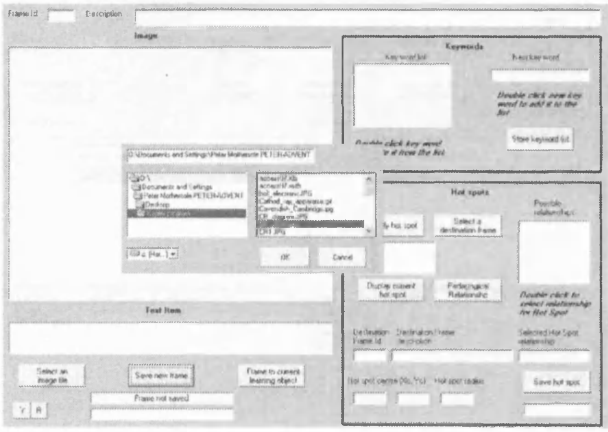

Figure 10: Creating a new knowledge frame.

- A description and appropriate keywords are then captured and linked to the frame.
- Circular hotspots are defined and stored.
- A frame may be inserted into a learning object, and optionally be specified as the source or destination of a named pedagogical relationship.

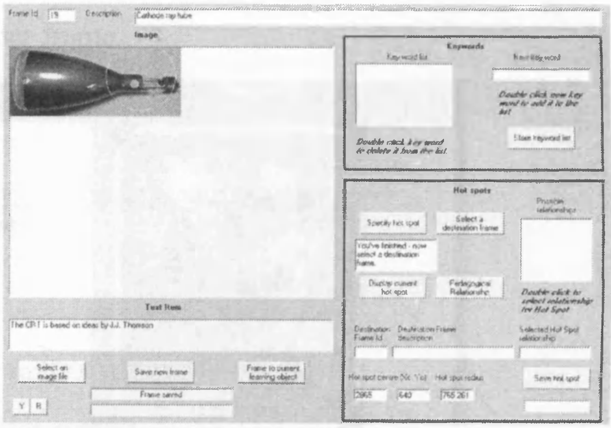

Figure 11: Editing a knowledge frame.

- Selecting a learning object uses a similar mechanism for searching as with knowledge frames.

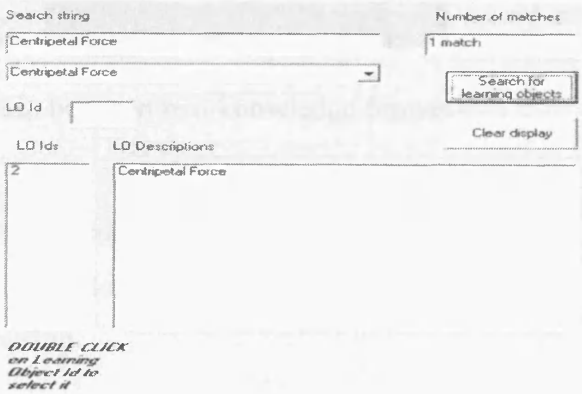

Figure 12: Searching for a learning object.

- A new learning object may be created, or an existing one edited using a common form. As with knowledge frames, learning objects are stored along with their description and set of keywords.
- The order of the sequence of knowledge frames within a learning object may be altered.

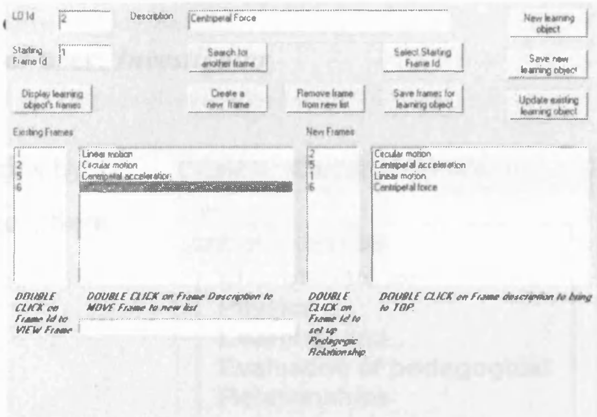

Figure 13: Editing a learning object.

- A pedagogical relationship may be defined between two frames, as illustrated below, or between a frame's hotspot and another frame.

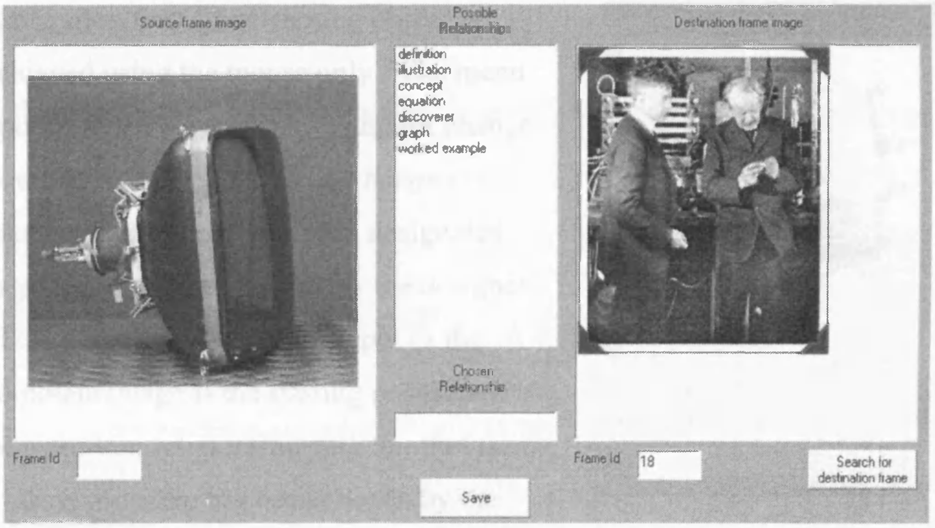

Figure 14: Defining a pedagogical relationship between two knowledge frames.

- Each pedagogical relationship belongs to particular type, and new types may be added. Further information concerning the reason for the pedagogical relationship is entered and stored along with the relationship.

KEPLER class of user: *Investigator*

- Investigating the stored knowledge begins by the user selecting a named learning object from KEPLER's main menu.

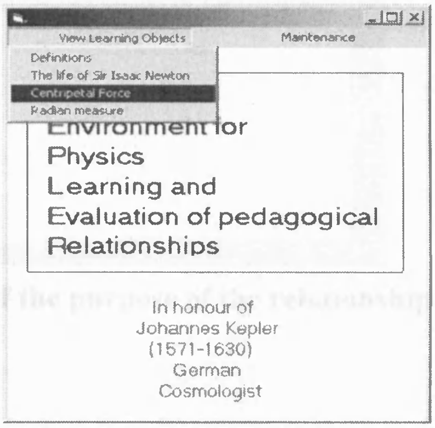

Figure 15: Investigating a learning object

- Navigation through a learning object is achieved using the mouse only. The menu options available to the investigator change as the mouse is moved over a *hotspot*; a localised area which has been designated as pedagogically important by the designer of the learning object. A hotspot or the complete image is the starting position of an important relationship with another frame. This relationship has been chosen by the designer for a pedagogical purpose.

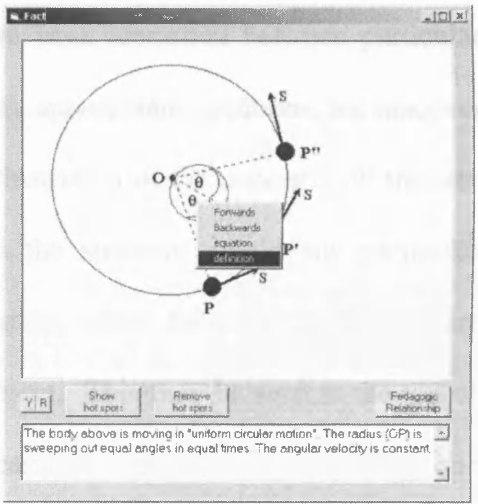

Figure 16: Which menu items are displayed depends on whether the mouse is in a hotspot.

- The investigator may decide to follow this relationship link to a new knowledge frame within another associated learning object.

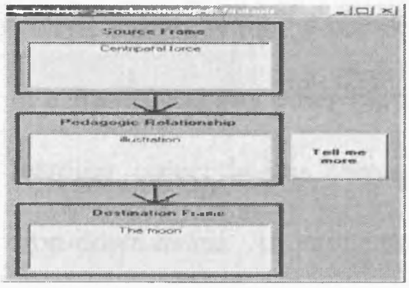

Figure 17: Pedagogical Relationship type

- The type of relationship and details of its pedagogical purpose may then be investigated.

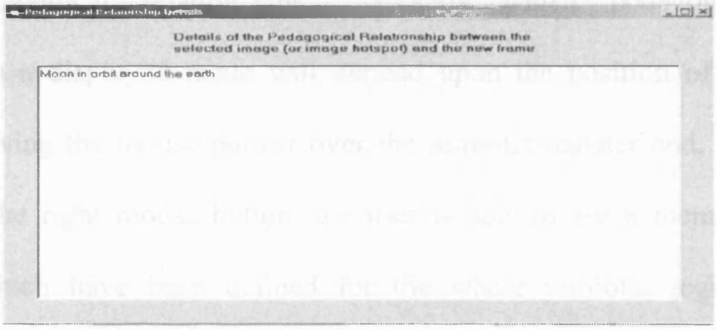

Figure 18: Description of the purpose of the relationship

Figure 19 shows a representation of learning objects related to the concept of *Centripetal Force*. Figure 20 shows the corresponding screenshots from the KEPLER program. In this simple example, pedagogical relationships have been identified between particular diagrams, showing the corresponding laws of physics, appropriate equations, the discover of the laws of physics, units of measurement and illustration of the concept. Within the various diagrams are important hotspots to which the students should pay particular attention. Since the knowledge frames are reusable, when they are used they are personalised by encapsulating them in a learning object. This may be seen at the top of Figure 19 and Figure 20 where there are four learning objects each containing one knowledge frame.

Once knowledge frames, each one containing a particular semiotic register, have been created, KEPLER enables a sequence of them to be defined as a named learning object. Additional pedagogical relationships may be defined between frames within a learning object, or between hotspots within the semiotic register of a frame, and any other frame. Investigating the knowledge represented within the learning object begins through selecting the name of the learning object from the initial drop-down menu. All navigation through the represented knowledge is achieved using the left and right mouse buttons. The left mouse button is used to select a displayed button or a particular item from a displayed menu. The right mouse button is used to display a menu of keywords representing available pedagogical relationships. Exactly which pedagogical relationships are available in a displayed menu will depend upon the position of the mouse pointer. Through moving the mouse pointer over the semiotic register and, at a particular position clicking the right mouse button, the user is able to see a menu of pedagogical relationships which have been defined for the whole semiotic register together with additional pedagogical relationships defined for the particular hotspot or hotspots in which the mouse is currently pointing. The various hotspots will have been defined for a knowledge frame's semiotic register when used in a particular learning object by the learning object's designer. The user may discover these hotspots through moving the mouse around the semiotic register, or alternatively the user may wish to display the positions of the hotspots by clicking a button on the frame display screen.

A particular learning object will have been designed to encourage the user to investigate the represented knowledge. Therefore there are several possible learning paths which might be followed by the user. However, referring to Figure 20, described below is an example of appropriate steps which the user might take. The particular learning path considered here is also represented in Figure 19, and details of the displayed frames are shown in the Appendix.

The user begins by selecting the name of a particular learning object from a drop-down menu on the first screen. In the case below, the user has selected *Centripetal Force*. The lettered items below (a), (b) etc. correspond to those in Figure 20.

(a) A frame containing a diagram description of *linear motion* is displayed. There are no hotspots on this particular diagram, clicking the right mouse button displays a menu with items: *forwards, backwards, concept.* The items *forwards* and *backwards* are available in every navigational menu. They refer to navigating to either the next or previous frame respectively in the current learning object. If the item *backwards* is selected when in the first frame of a learning object, since no frame exists logically before the first, a pop-up warning message is displayed. In a similar way, a warning message is displayed if the user selects the item *forwards* when in a learning object's last frame.

(b) In this example, the user has chosen to select the menu item *concept*; which indicates that behind this diagram, concerning linear motion, there is in fact a familiar physics *concept*. On selecting the item a new frame appears, the first in another learning object concerned with *Newton's Laws of Motion*. This learning object could have been selected directly from the initial drop-down list of available learning objects. The current knowledge frame shows the definition of *Newton's First Law of Motion*, familiar in many physics textbooks. Again, there are no hotspots in this particular semiotic register. However, from any mouse position in this frame a menu appears with items: *forwards*, *backwards*, *discoverer*.

(c) The user may wish to move forwards through this learning object displaying in turn details of *Newton's other laws of motion*.

(d) However, the user may wish to select menu item *discoverer* and move into yet a further learning object called *Sir Isaac Newton,* which contains a sequence of knowledge frames giving some details of *Newton's life*. Each of these frames contain images. Again, this learning object could have been selected explicitly from the initial drop down menu of learning object names.

When navigating through a learning object only a single knowledge frame is displayed. That is the next frame replaces the previous one. However, moving to a new learning object does not close the previous learning object, hence at this stage in this particular learning path we would have current knowledge frames from the three different learning objects so far opened. Because of this feature, it is simple to return to the very first frame

(a) within the original learning object on *Centripetal Force*. This can be achieved by closing unwanted knowledge frames or moving them to the side of the screen.

The user could now navigate forwards through the learning object going from (a) to (e). This time the diagram in frame (e) does contain a hotspot which is localised around the *angle measured at the centre of the displayed circle*. Selecting the navigation menu when the mouse is inside the hotspot displays items: *forward*, *backwards*, *definition*. Following the extra hotspot pedagogical relationship *definition* will open a new learning object concerned with *Radian Measure*, displaying the first of its knowledge frames (f).

The user may wish to select the *forward* link from frame (e) to frame (g), which has three hotspots. If the user were to display the position sensitive menu centred on the diagram of the *orbiting mass* and selecting menu item *definition* the software would navigate to a learning object which in fact only contains a single frame. This frame contains an image of the *standard kilogramme in Sevrès, France*.

Whenever a new frame is displayed the user may interrogate details of the relationship between the source and destination frame. This interrogation is a two-step process. When the user selects an appropriate button on the destination frame, the descriptive window (Figure: 17) is displayed, This just identifies the titles of the source and destination frames, together with the named pedagogical relationship. The user may request further information by clicking an appropriate button. A further window is then displayed containing a fuller description of the pedagogical relationship between the represented knowledge (Figure: 18).

Since the information displayed by KEPLER is derived from data within a relational database, the teacher who designed this particular knowledge representation could explain in depth the purpose for the pedagogical relationship.

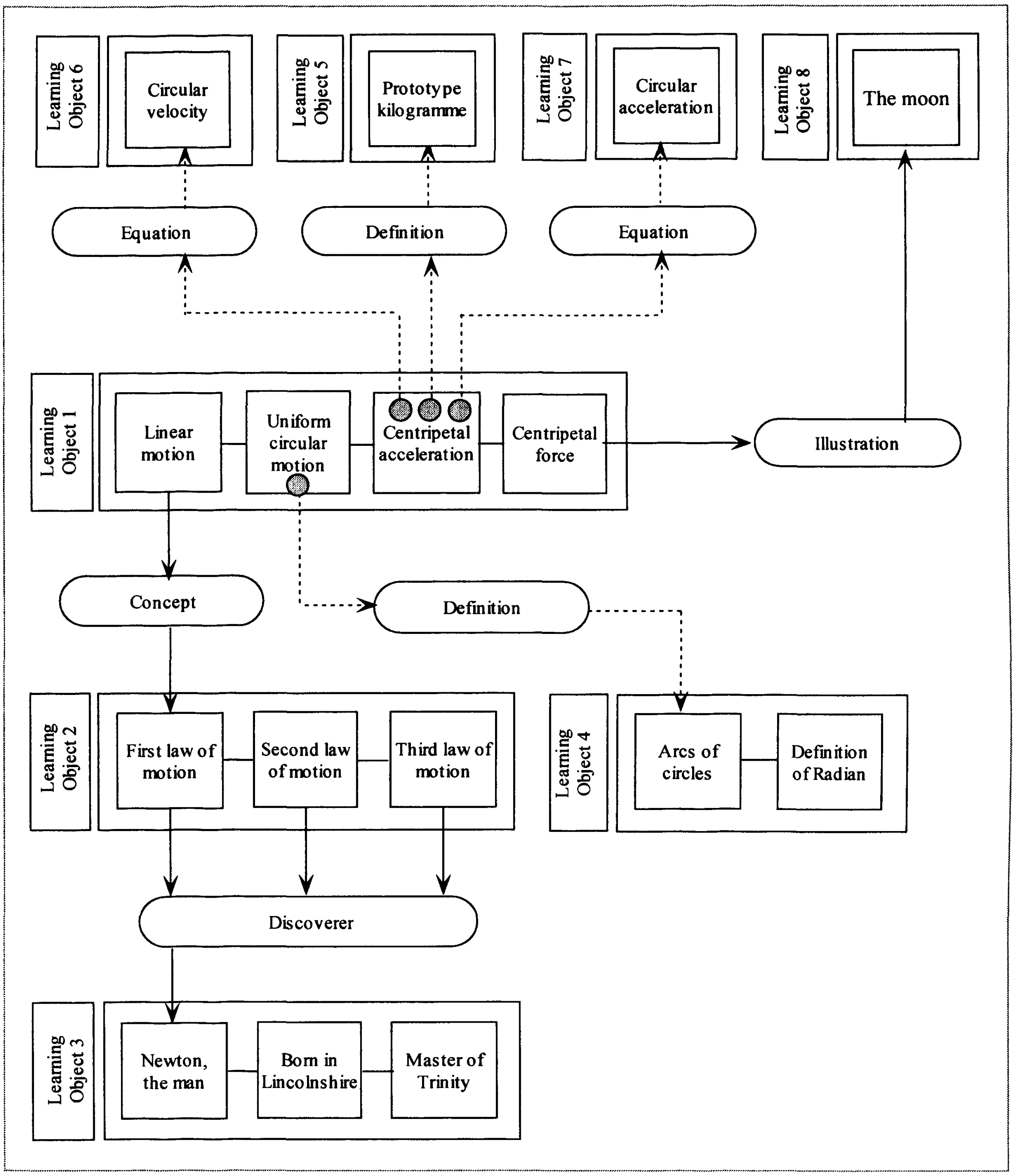

Figure 19: Diagram of a KEPLER knowledge structure consisting of learning objects, frames and pedagogical relationship.

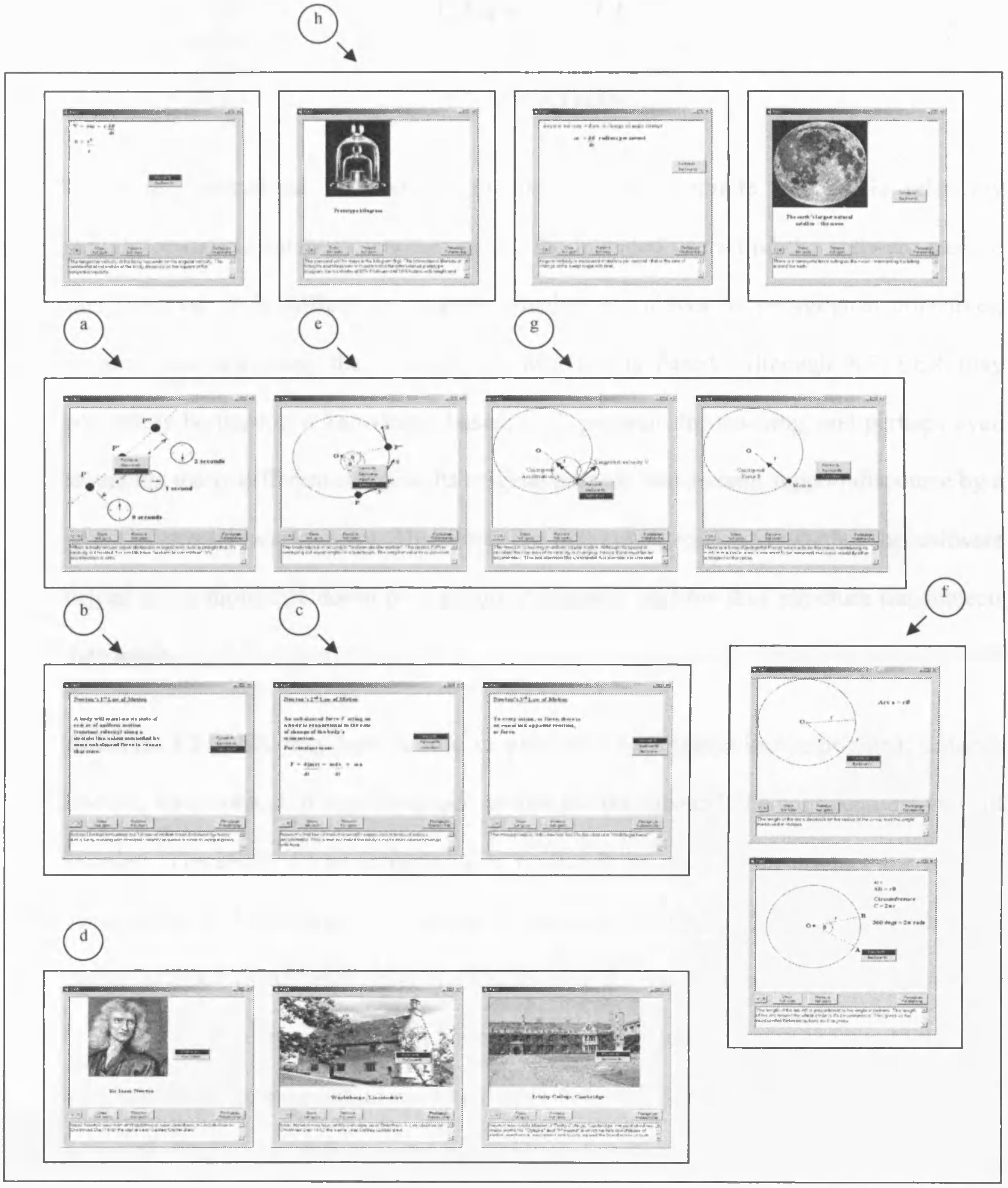

Figure 20: Example dialogue of knowledge frames corresponding to the KEPLER knowledge structure in Figure19.

Chapter 11

EVALUATION

Evaluating educational software is far from being a simple task. It is relatively straightforward to establish whether or not the intended users find the software easy to use. However, it is difficult to measure whether it achieves its pedagogical objectives, without also criticising the concepts on which it is based. Although KEPLER may potentially be used as a knowledge-based, CAL program for teaching, and perhaps even assessing, many different subjects, its original purpose was to help support discourse by a group of pre-service teachers. Therefore, the first consideration is whether the software helped to promote discussion by a group of teachers on how they structure the subjects they teach.

Although KEPLER may have a role to play in a more behaviourist-oriented, didactic learning environment, it was developed against the background of a constructivist view of learning. Therefore it was intended that KEPLER be used as an artefact for the co-construction of knowledge by a group of learners (Vygotsky, 1978). Considered as a digital artefact (Jonassen, 1994), KEPLER was designed to be a prototype tool for helping to build a representation of context-related knowledge. It was envisaged that this computer-based representation would aid learners in acquiring understanding of particular concepts. Therefore, the second consideration is whether the software did enable a knowledge structure to be created, edited and viewed. Although the bias of the thesis has been towards the teaching of physics, there are other subjects which share similar emphasis on abstraction, the use of analogues, representation using semiotic registers, scientific experimentation etc.; namely the other sciences, computing, technology and, to a lesser extent, mathematics. Therefore, if KEPLER proved to be an aid to developing knowledge in any of these subjects, it is considered to be valid .

Locating possible evaluators was achieved through the Institute of Physics, a professional body and learned society, and also through one of the many Internet-based forums; the one chosen having members who were teachers interested in teaching concepts in science. Predictably, although it was relatively straightforward to identify current and past colleagues who could help in testing the software, it was harder to locate new contacts for the same purpose. Of course it was even more problematic to persuade contacts to find sufficient time to test and evaluate the software.

However results were obtained from evaluators who had experience in teaching a science subject to Advanced Level, teaching a science subject to undergraduate level, or helping to tutor new science teachers. Each of the evaluators had been sent a CDROM containing the following items. These items were also made available from a College web site.

- an executable copy of KEPLER, to run on any standalone PC using the Windows XP operating system
- a copy of the relational database for Microsoft Access 97
- a copy of the relational database for Microsoft Access 2000
- a copy of the source program written in Visual Basic 6
- a small library of JPG image files
- documentation (source program listing, ER diagram, "Get you started" guide to running the program – as show in the Appendix).

Problems did arise in installing the software on some PCs due to a variety of causes. The majority of problems were eventually overcome and the evaluators were requested to attempt to complete the following tasks.

As an *investigator* class of user.

- Select any learning object from KEPLER's main menu, investigate the various routes through the knowledge structure.
- Consider carefully how difficult the program is the use: especially in terms of navigating through the knowledge.
- Also consider whether the software might be of some use in particular types of learning situation: e.g. discovery learning.

As a *modeller* class of user.

Use KEPLER to perform the following tasks, using any documentation where available. When changes have been made, test the learning objects and knowledge frames by acting as an *investigator*.

1. Find a particular knowledge frame and then:
   (a) edit the knowledge frame by adding/deleting keywords or changing the description
   (b) edit the knowledge frame by adding/deleting pedagogical relationship to another frame
   (c) edit the knowledge frame by adding/deleting a particular hotspot in the frame's image
2. Create a new knowledge frame by first selecting an appropriate image, and then repeat steps 1 (a) to 1 (c) above.

3. Find a particular learning object and then:

   (a) edit the learning object by adding/deleting knowledge frames

   (a) edit the learning object by changing the sequence of knowledge frames.

4. Create a new learning object with an appropriate description and keywords.

   Repeat steps 3 (a) and 3 (b) above.

Because of the initial problems, the nature of the software, the complexity of the tasks, and a range of IT skills among the evaluators, contact by email or telephone was encouraged, and it was felt that interviews would be the most appropriate way to capture any feedback from the users. In most cases these were done by telephone at various times during the evaluation process. Comments were noted, analysed and aggregated into the points below.

Software interface (*investigator*)

The majority of users found this interface was easy, and quite fun, to use. It required minimal IT skills. Not all users were satisfied with the choice of colours, and some considered that the size of the text fonts should be increased. The positions of the hotspots may be made visible; some users wished this feature to be removed, forcing the user to discover where they were placed. When investigating knowledge frames inside the learning object, some users did lose their way.

Software interface (*modeller*)

Only a minority of the users found this interface straightforward to use. The software assumed a relatively high IT ability, which only some of the evaluators possessed. Understanding exactly what was meant by a learning object, knowledge frame and pedagogical relationship was essential to complete the exercise. The main problem when creating a new knowledge frame was finding a relevant image. Users had to either search the World Wide Web or create their own diagram and then save it as an image file. This was found to be very time-consuming. When creating a new learning object it was necessary to draw a series of diagrams as a plan before using the software. Several users began by drawing a concept map and then creating one or more learning objects for each concept. On the whole, using the program to create a knowledge structure was very time-consuming.

Discussions between users

Some of the users were overwhelmed by the number of different relationships possible between, say, two frames. Some users did indicate that using the software did get them to think more carefully about relationships between the information. There were comments about the area and shape of a hotspot; the program did not *see* the localised area of interest in exactly the same way as the teacher. Even irregularly shaped hotspots are implemented as circles in KEPLER.

Recommendations

Analysing the various comments does lead to a useful checklist of desirable program features, and possibly particular ways in which KEPLER might be better employed. The most important changes are:

- There needs to be a radical redesign for the *modeller* form-based interface. The current interface is too complex, and it is debatable whether a simpler more generalised interface which would enable either learning objects, knowledge frames, or pedagogical relationships to be specified.
- Since many users found it useful to draw concept maps prior to designing learning objects and frames, the program's interface should start with a concept map. The user would then select a particular concept symbol, which could be considered as a high-level hotspot, and the software would enable a graphical representation of a learning

object. As knowledge frames are selected from the library, or created by the user, they may be *dragged* to the learning object diagram. The graphical interface might look something like the diagram in Figure 19.

- There is an opportunity for creating a database of images which may be accessed via the World Wide Web. If there are no copyright infringements, the images could be reused for any reason including the creation of new knowledge frames. This is where the semantic Web project clearly has a role to play in setting the standard for meta data descriptions of the various image files. A user would then be able to search for a relevant image file by entering appropriate semantic keywords.
- Collaborative learning might be achieved by enabling a group of students to have access to a *shared* copy of a semiotic register over the World Wide Web. If a particular student downloads and edits *their* copy of the register, there must be a mechanism for other students' copies to be refreshed.
- Representing details of a regular shaped hotspot for a particular knowledge frame is possible, but would of course require the storage of more coordinate data.

Chapter 12

CONCLUSION

Educational systems are always in a state of flux, and indeed perhaps they should be. Whether their role is considered to be reactive to the changing needs of society, or proactive as a force for change, they are complex, human, often frustrating, but endlessly fascinating to us fortunate enough to work in them. One of the most significant changes still taking place in many educational systems is an adjustment of the roles of learner and of teacher, and of the relationships between them. For a long time it has been realised that, although teaching may be bound in space and time, learning is not. Despite realising this, when designing systems which support teaching and learning, we have tended towards timetabling students to be present at a particular location together with a teacher. Of course, this model was seen as efficient since certain resources, including the teacher's time and attention or cognitive focus, could be shared amongst the various attending students. In fact that statement is not exactly valid. In a traditional lecture, the teacher's focus is not necessarily shared by the individual student, since the teacher may not accept feedback from individual students, but instead consciously address the group. In a traditional classroom, the teacher's focus may change more dynamically, in that there may be times when the interaction with the group is replaced by a personalised interaction with an individual student or subgroup.

One might expect that the preamble above would be used to support an argument for a fundamental change away from relying on the presence of a teacher. Perhaps, because an experienced teacher is unavailable, or money must be saved, or there is a need to cater to very large student groups, an educational administrator might consider replacing the teacher by a computer-based learning system. But, if the aim is quality learning, the relationship between the subject teacher and the student will require cognition which no computer can yet simulate.

If we attempt to try to model any part of the teacher's perception, problem solving or communication, the complexity soon becomes evident. From observing facial expressions in order to find evidence of student understanding, through predicting the consequences of a particular teaching action, to having empathy with the student who does not understand a diagram, the teacher, to use AI terms, really is an *intelligent, highly adaptive, heuristic, context-sensitive* system.

But no matter how intelligent the teacher is, that intelligence alone is insufficient to guarantee learning. Of course, the teacher might be able to convince a student into remembering some aspect of the subject. But for more than just shallow recall, the student's active participation in the learning process is paramount. It is interesting to see how various ways of learning, perhaps once familiar outside school, have returned to school. The familiar everyday experiences of interacting with lots of different people, in different situations, is a vital, daily learning source. The different roles we play in situations outside school or university do foster learning. Therefore students should indeed gain if their learning role is adaptable and problems considered are as real as possible.

Of course, the idea of enriching the student's experience in the learning environment is supported by the constructivist view of how learning takes place. Learning is not an isolated activity. That is to say three different things. Firstly, learning one subject cannot be divorced from learning other subjects simultaneously. For example, all physics lessons are language lessons. Secondly, learning one subject requires us to bridge from, as well as lead towards, other subjects. For example, using a particular analogical model to illustrate some aspect of physics, requires that the domain of the analogue has already been studied. Thirdly, learning is achieved in and through groups of learners.

But, if learning within a group of science students enables them to introduce new ideas, some science teachers would be concerned with the validity of those ideas set against accepted scientific truths. But, in science, even though there are provable facts, each scientist understands the concept behind such facts in a highly personalised way. If the science teacher wishes to encourage collaborative learning, it does not mean that their role is to stand aside and allow any new ideas to emerge without being challenged. Indeed, encouraging students to challenge ideas is an important part of science. However, being able to fulfil this difficult, more adaptable role requires the teacher to have a growing knowledge base of science concepts and PCK.

The aim behind this research was to consider the nature of the conceptual knowledge which a physics teacher must have to be effective. This conceptual knowledge is not knowledge of just physics. Instead, it is posited that this conceptual knowledge is a framework of interrelated subject ideas, where in addition to taxonomic relationships within physics, other relationships have been forged for purposes of learning. It might be true that, as the physics teacher gains more experience, the more useful physics ideas become strengthened, while others fall into disuse. It might also be true that, as the teacher's subject knowledge develops, as well as their pedagogical knowledge, the quantity and diversity of purposeful relationships between the physics ideas increases.

At the heart of this work is the stress made on the rich, diversity of relationships used by scientist and science teacher. Making sense of the world requires us to process not just our observation of things, but the relationships between those things. This is part of perception; a method of abstraction in which new observations are recognised as already having a category in which to place them. Often, without us even being fully aware, we focus on different relationships between things, depending of course on the context. If the need arises, recognised relationships may be weakened, while others are strengthened. There is an interesting experiment which is usually enjoyed by younger children. Pick up a pen in one hand and a piece of paper in the other. Then ask the children to describe five ways in which the two objects are related. Alternatively, ask them in what ways the two objects are similar. It is remarkable to realise how complex the relationships can be just between two everyday objects. The task becomes even more creative if the two objects chosen are dissimilar, e.g. a lion and a banana.

The relationships are of course mental constructs, as are the purposeful pedagogical relationships which were considered for the physics teacher. The research suggested that pedagogical relationships are important in teaching. But in order to try to test out this hypothesis it was necessary to enable the target audience to somehow interact with the proposed model. This cannot be done directly of course. Therefore it was necessary to create a representation of the pedagogical model using software; hence KEPLER. For the teacher, pedagogical relationships are inter-conceptual and intra-conceptual. But when representing this model using software, something more concrete than concepts had to be interrelated. Because of the nature of how scientists construct domain related knowledge, relating together concepts was implemented as relating together those physical artefacts which are used to help develop concepts. Therefore the user, student or teacher, was able to investigate relationships between semiotic registers as a step towards investigating relationships between concepts.

The positive results from trialling KEPLER were two-fold. Firstly, it was seen as being of some use to be able to discuss how one teacher describes the interrelationships between concepts, modelled as relationships between semiotic registers. Secondly, stressing the pedagogical importance of even simple diagrams, was an encouragement to all concerned to consider how diagrams are used. There is a need for further research into the nature and use of diagrams as a means of knowledge construction in constructivist learning. It should be fruitful to investigate how diagrams should be designed for pedagogical use, how they are imbued with status and value by students, and perhaps above all, how they may be interpreted differently by students and teachers.

However, the main criticism of KEPLER was that it was difficult to use it to create learning objects and knowledge frames. A form-like interface had been designed for KEPLER, and it was found to be difficult for some users. Therefore the next important stage will be to re-design KEPLER, primarily by creating a more friendly, more graphical interface; perhaps similar to current concept maps.

Appendices

A Pedagogical Knowledge-Sharing Environment For Novice Physics Teachers Based On Modelling Relationships Within Pedagogical Content Knowledge (PCK)

The epistemology of Physics as experienced by a physics teacher may differ somewhat from that of the non-teaching professional physicist. There is of course some overlap between the two, but the question arises as to the nature of the knowledge which an experienced physics teacher draws upon in order to teach students?

Many workers who have researched into the challenges in teaching of a scientific subject such as physics, in school or at the university level, consider that in order for a student to be successful in problem solving, they must have acquired an appropriate conceptual framework (e.g. Mellema, 2001). Shulman (1986) introduced the concept of *pedagogical content knowledge* (PCK); an epistemology relating subject (or content) knowledge with pedagogical (or curricular) knowledge. The focus of the research for this PhD thesis has been to consider the requisite elements of a conceptual framework based on PCK for an experienced physics teacher and evaluate its design and deployment within a pedagogical knowledge-sharing environment.

In contrast to this *top-down* approach, the current research also considers the nature of, what is here termed, *knowledge frames,* common in all physics teaching. Such knowledge frames are readily seen in any physics textbook, academic paper or teacher/student notes. There are knowledge frames which correspond to the ways physicists encapsulate declarative knowledge about a subject; e.g. through equations, diagrams, graphs, stated hypotheses, experimental conclusions etc. There are also knowledge frames used when teaching physics; such as questions and answers, worked examples, illustrations of concepts, analogues, counter examples, etc.

The research further explores how an experienced physics teacher *relates* such knowledge frames one to another. These relationships, called here *pedagogical relationships,* are purposeful relationships enabling the teacher to build an appropriate pedagogical architecture for the domain (Physics).

A prototype computer program (KEPLER[5]) has been designed and implemented to enable an experienced teacher to build the architecture of knowledge frames for teaching a particular topic in Physics. The knowledge frames may be contained within a larger didactic structure or *learning object*. Each knowledge frame is built from an image file (e.g. JPG, GIF, BMP) and a text file (although theoretically any multimedia data may be included). The teacher is able to specify pedagogical relationships between one frame and another, or between particular parts of the image (termed *hot spots*) and another frame.

This research considers that, although the paradigm of constructivist learning is based on a student actively building their own concepts, and not passively receiving knowledge (von Glasersfeld, 1987), learning may take place through interacting with the computerised architecture built by an experienced teacher. The computerised architecture, as well as the knowledge frames within it, may be considered as examples of what in Activity Theory are termed *culturally mediated tools and signs* (Vygotsky, 1978).

KEPLER: **K**nowledge **E**nvironment for **P**hysics **L**earning and **E**valuation of pedagogical **R**elationships

In this way it is hoped that something of the experienced teacher's conceptual framework or model of the subject is transferred through students interacting with the software as a mediating *negotiation space*

Such a software environment may be particularly useful for those being trained as physics teachers. Such novice teachers may be able to investigate the architecture built by an experienced physics teacher. They may then consider the nature of the purposeful pedagogical relationships which have been built in, as well as which image *hot spots* are important. It is further hoped that the software may be a vehicle for constructionist learning (Papert, 1993) through the novice teachers adding new knowledge frames to an existing architecture, or building their own version, and then discussing the contents.

Request

I am looking for university lecturers who are concerned with teaching new physics teachers. I would like them to look critically at the software over the next month or so and answer some questions about its potential use in communicating *pedagogical content knowledge*.

I can be contacted by email at: peter.mothersole@northampton.ac.uk

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KEPLER

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KEPLER: **K**nowledge **E**vironment for **P**hysics **L**earning and **E**valuation of pedagogical **R**elationships

Background

Several educators concerned with Physics teaching consider that the pedagogy should focus on the active construction of a conceptual framework as well as the accompanying mathematical and problem solving skills (e.g. Mellema, 2001). Look through almost any Physics book, notes or academic paper, and you are likely to recognise the common building blocks of Physics knowledge; equations, particular types of diagram, graphs, tables, etc. In addition there may be the building blocks of Physics pedagogical knowledge, such as explanations of concepts, stated hypotheses, theories and laws, problems and answers, illustrative or even analogical examples. Hence there appears to be a commonly used ontology of knowledge *objects* for the teaching and learning of Physics.

The question arises concerning the nature of the possible relationships between these so called knowledge objects? How are they used by an experienced Physics teacher? The term *pedagogical content knowledge* (PCK) was introduced by Shulman (1986) to identify a teacher's cognitive understanding of subject matter. It was seen as being separate from subject or content knowledge, and curricular or general pedagogic knowledge. The task of the teacher may be considered as selecting knowledge from separate knowledge bases of subject matter, pedagogy, and context, and integrating them to create effective learning environments. An expert teacher may be observed to move between these knowledge bases in a seamless way, giving evidence of the existence of a single knowledge base for teaching, namely PCK (Gess-Newsome, 1999).

KEPLER is a computer program written primarily for use by novice Physics teachers. The software enables a series of *knowledge objects* (consisting of a chosen image and text description) to be built into *learning objects*. An image could typically be a photograph of some apparatus, a labelled diagram, a chart or a graph. The whole or part of an image (an image *hot spot*) can be related to any other knowledge frame. This relationship is chosen by the teacher for typical pedagogical reasons, hence it is called a *pedagogical relationship*. In Physics such relationships might link a concept to an equation, a law to its discoverer, a measuring device to its application, a concept to an illustration of that concept, and so on. The software enables such a relationship to be chosen and extra pedagogical information (e.g. perhaps reasons for choosing a particular relationship) can be added.

It is envisaged that an experienced Physics teacher trainer might use the software to communicate their view of a particular sub topic to their students. The software can be used to build such a knowledge model, and will enable that knowledge model to be interrogated by others.

The mouse-driven user interface is written in © Microsoft Visual Basic 6. Images are stored as separate JPG, BMP or GIF files. Text, keywords, definitions of Frames and Learning Objects, pedagogical relationships etc are stored in a © Microsoft Access 97 database.

Main menus

Select from these menus using the LEFT MOUSE BUTTON

- **View learning objects**

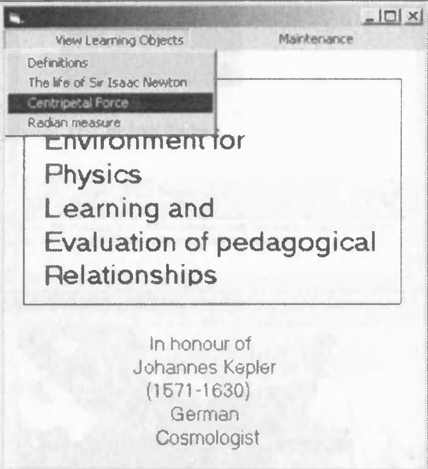
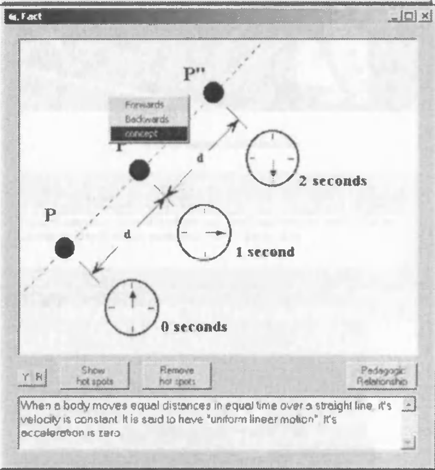
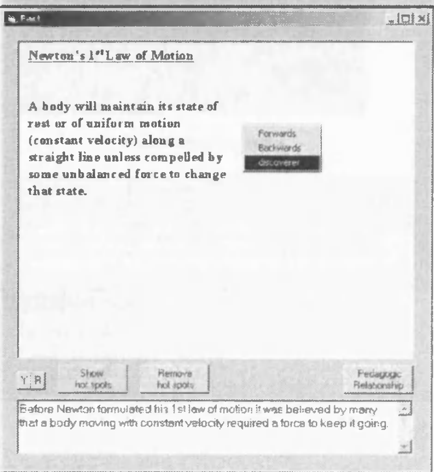
Definitions
Displays the definition of a Frame and a Learning Object
The life of Sir Isaac Newton
Centripetal Force
Radian measure
Examples of very simple Learning Objects containing Frames. These Learning Objects are linked together – see "Investigating a Learning Object" below.

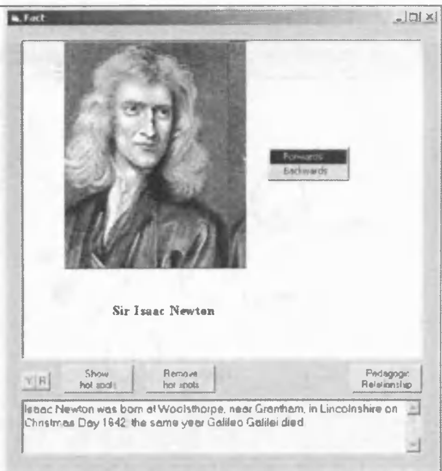
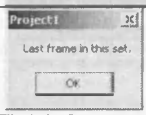
- **Maintenance**

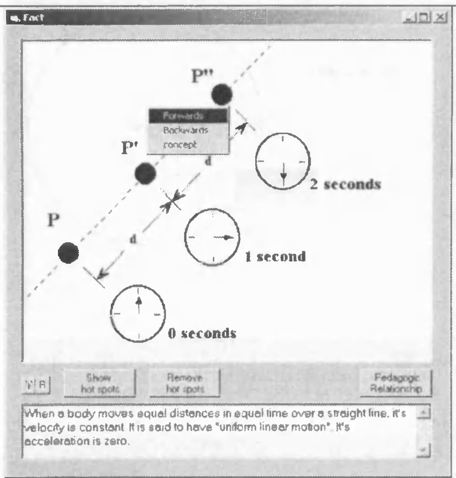
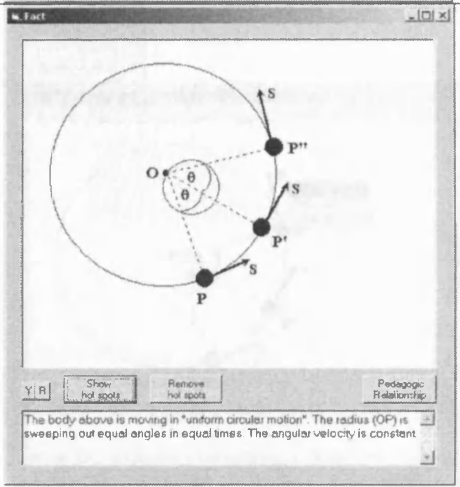
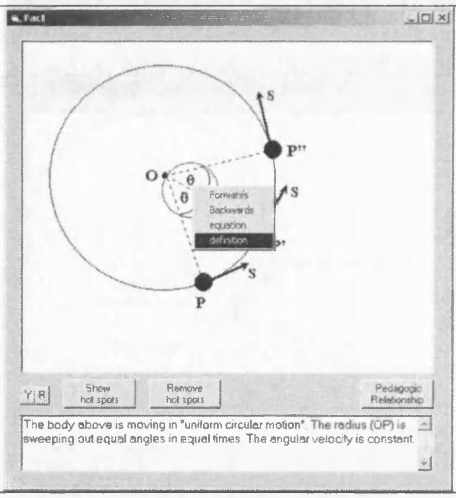
About KEPLER
Displays version number, date and author.
New Frame
Edit Frame
Enables the creation and editing of a knowledge Frame (with image, text items and key words). Pedagogical relationships between the image and another Frame can be added. Any number of hot spot areas can be specified for an image; each of these can be associated with a pedagogical relationship which links to a further Frame.
New learning object
Edit learning object
Enables the creation and editing of a Learning Object (with its associated key words). The Frames and their presentation order can be defined for the Learning Object. New Learning Object names are added to the "View learning objects" menu above.

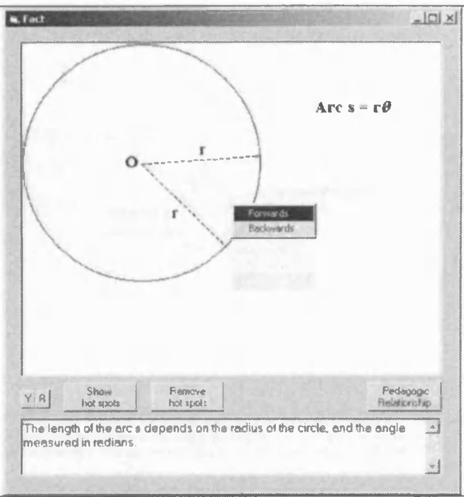
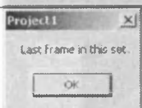
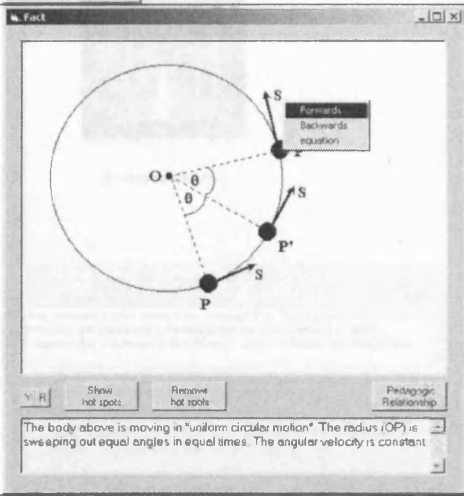
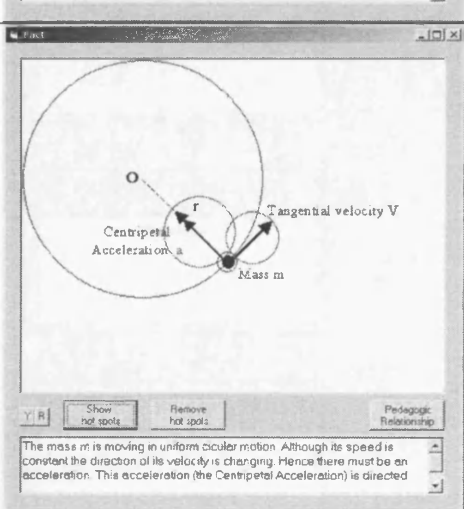
Investigating a Learning Object

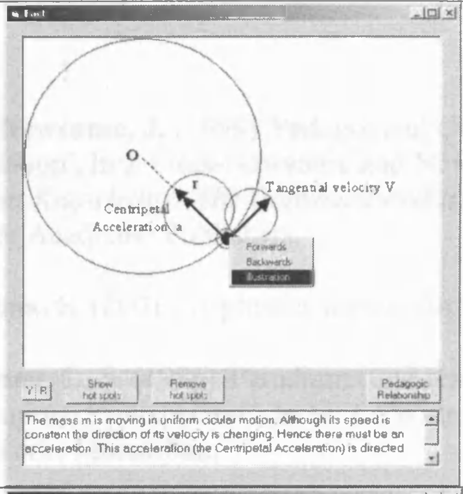
Step by step tour

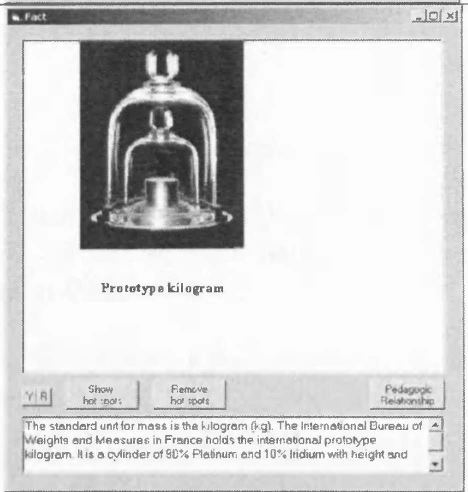
<table>
<tr><th>Step</th><th>Display</th><th>Guide</th></tr>
<tr><td>1</td><td>
</td><td>Use your LEFT MOUSE BUTTON to select the Learning Object "Centripetal Force".</td></tr>
<tr><td>2</td><td>
</td><td>The first Frame of this Learning Object will be displayed.
Click the RIGHT MOUSE BUTTON anywhere on the image. A menu will appear. Use your LEFT MOUSE BUTTON to select "concept". That is you are requesting to know the concept behind uniform linear motion which is the subject of the current Frame.</td></tr>
<tr><td>3</td><td>
</td><td>A Frame showing a definition of Newton's 1st Law of Motion. Click your RIGHT MOUSE BUTTON and select "discoverer". If you had chosen "Forwards" you would be moving through Newton's Laws of Motion.</td></tr>
</table>

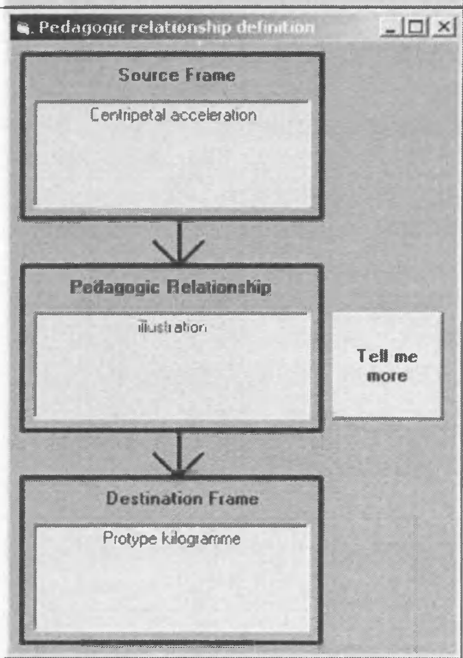
4		Sir Isaac Newton, the discoverer of this law of motion. You are now actually in another Learning Object. Use your RIGHT MOUSE BUTTON to display the menu and select "Forwards" to move to the next Frame of this Learning Object "The Life of Sir Isaac Newton".
5		Here's the next Frame showing where Newton was born. Use your RIGHT MOUSE BUTTON to display the menu and select "Forwards" again to move to the last Frame of this Learning Object.
6		Here's the final Frame of this Learning Object. If you again display the menu and select "Forwards", as there are no more Frames in this Learning Object, you will get …
7		this. Close the windows until you see the following original Frame.

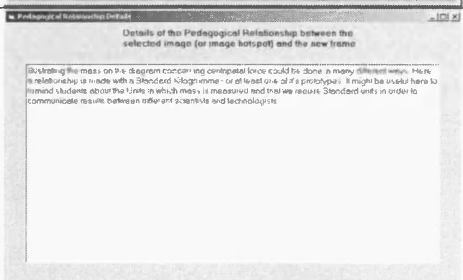
8		Now we are going to move through this Learning Object "Centripetal Force". Use your RIGHT MOUSE BUTTON to display the menu, and select "Forwards".
9		In this Frame click (LEFT MOUSE BUTTON) on "Show hot spots". Now move the mouse over the displayed circle and press your RIGHT MOUSE BUTTON. Move your mouse outside this hot spot circle and again press your RIGHT MOUSE BUTTON. You can see that an image can have different active hot spots which affect the displayed menu.
10		With your mouse over the "hot spot", click the RIGHT MOUSE BUTTON and use your LEFT MOUSE BUTTON to select "definition". Here you are requesting a definition of the angle **θ** in the diagram.

11		You will now see the first Frame in a Learning Object concerned with "Radian measure". Use your RIGHT MOUSE BUTTON anywhere in the image to display a menu. Select "Forwards" using your LEFT MOUSE BUTTON will show you that there is only one Frame in this Learning Object.
12		Click on OK and then close the "Radian measure" Frame.
13		From this Frame move Forwards.
14		Display the image "hot spots".

<table>
<tr><td>15</td><td>
</td><td>Display a menu above the centre "hot spot" – over the small mass.

Now select "illustration".</td></tr>
<tr><td>16</td><td>
</td><td>You have used the pedagogical relationship "illustration" to display a Frame illustrating something about the "mass".

Now use your LEFT MOUSE BUTTON to select "Pedagogical Relationship" to learn more.</td></tr>
<tr><td>17</td><td>
</td><td>This displayed Frame just indicates the location of the current Pedagogical Relationship. Its between the Source Frame "Centripetal acceleration" and the Destination Frame "Prototype kilogram".

Now use your LEFT MOUSE BUTTON and select "Tell me more" to display possible pedagogical reasons for this relationship.</td></tr>
<tr><td>18</td><td>
</td><td>This is the end of the quick tour of the program.

You can close all of your Windows now.</td></tr>
</table>

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