Teaching Introductory Thermal Physics through Problem Based Learning

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Declaration

I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of Master of Science is entirely my own work and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my own work.

Signed: Rebecca Tracey | ID Number: 99391031

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Teaching Introductory Thermal Physics through Problem Based Learning

The development and delivery of an introductory thermal physics module taught through Problem Based Learning (PBL) in a lecture-based curriculum is reported on. The development and implementation of the module is illustrated through discussion of the problems and students responses.

The PBL methodology is compared with traditional lecture style teaching and the educational theories that the methodologies stem from are discussed. Examples of how PBL has been used to teach physics, along with the assessment of the thermal physics module are used to appraise some of the benefits of PBL, particularly increased student motivation, development of effective groupwork skills and increased understanding, in light of students' development. The impact of PBL on students' learning is demonstrated through examples of their thinking and analysis of pre and posts test results with those reported in literature.

The differences between the approach of Science Education students and Physics students to the PBL module and any affect this had on their learning is discussed. Finally, students' opinions of the module are examined and recommendations for its improvement are suggested.

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Chapter One Problem Based Learning In Context

1.1. Introduction

We report on the implementation of Problem Based Learning (PBL) as an alternative methodology in teaching introductory thermal physics and assess the impact of PBL on students' understanding and attitudes to learning. The aim of this work is to survey the efficacy of the PBL module as it is delivered currently and to provide recommendations for further improvements to it in the future.

Traditionally students are presented with material and are then required to apply this through completing end of chapter exercises. One of the defining characteristics of Problem Based Learning is that the students are deliberately presented with the Problem at the start of the learning process.

The PBL module reported on was delivered to first year undergraduate physics and astronomy students and second year science education students (training to be science teachers). Six PBL Problems were developed to cover the topics of a traditional introductory thermal physics lecture module, e.g. heat transfer, kinetic theory, Ideal Gas Law, and laws of thermodynamics. Four of these Problems had been designed and delivered previously and we report on the development of two more.

A qualitative and quantitative assessment of students' attitudes before, during, and after delivery of the PBL module is presented in chapter two. Students' answers to the Introductory Problem gave us an insight to their attitudes towards PBL before the module began. During the module students' attitudes to the learning process were assessed by observation and discussion during PBL tutorials, as recorded by the facilitators. At the end of the module a questionnaire was given to students to ascertain how completing the module had affected their attitudes towards PBL.

The development of students understanding and knowledge was assessed during each of the six Problems. This was evaluated using pre and post tests, end of Problem reports, oral presentations and a final written examination. The results of this evaluation and comparisons with similar studies reported in literature are discussed for each Problem in the relevant chapters.

In this thesis the comparison between PBL and traditional teaching methodologies are discussed. The difficulties we had in implementing PBL, as well as the advantages that were experienced are outlined. This research does not provide a unique solution for teaching an undergraduate thermal physics module, however we make recommendations for improvements that should increase student learning. Further research is necessary, to address all of the concerns that arose during the development, implementation and assessment of this module, in order to gain maximum benefit from this methodology.

1.2. Learning theories and teaching methodologies

1.2.1. Overview

It has been stated that third level education is not expected to develop students' knowledge alone; rather it is intended to provide students with the skills necessary to be successful in their future careers and so should equip students to[1]:

- Communicate
- Retrieve information
- Use technology
- Apply new knowledge and skills
- Define problems and reach solutions
- Work effectively with others
- Address specific problems in complex settings

To develop these skills it is necessary to use an appropriate teaching methodology. Traditionally, lecture has been the main teaching methodology used at third level and it is still predominant today[2]. However, lectures do not effect the development of these skills (see section 1.2.3.) and so it is necessary to address the way in which students are taught to achieve this aim.

Teaching methodologies are informed by learning theories. Before an effective method of teaching is developed it is first necessary to examine the way that people learn, and what the instructor would like them to learn. The methodology that is employed in teaching reflects the instructors' view of learning. There are many theories of learning[3], but the two most pertinent to the lecture and PBL methodologies are behaviourism and constructivism. Behaviourism, as its name suggests, asserts that learning is a change in behaviour, brought about by a response to a stimulus. On the other hand constructivism is based on the belief that learning is an active process in which learners construct new ideas or concepts based upon their current and past knowledge. The learner selects and transforms information, constructs hypotheses, and makes decisions, relying on a cognitive structure to do so.[4] As these theories view learning in very different ways, the methodologies that stem from them are also very different.

1.2.2. The behaviourist theory of learning

The underlying principle of behaviourism is that animals and humans can be conditioned to give a certain response to a stimulus. Ivan Pavlov[5] was the first to carry out research into behaviourism. He used experimental work with animals, through which he developed his classical conditioning theory. The basis of this theory is that animals and humans give natural or unconditioned responses to natural stimuli. In one of Pavlov's experiments this was a dog salivating when presented with food. When a conditioned stimulus (in the experiment the ringing of a bell) is presented there is initially no response. However through ringing the bell every time the dog was presented with food, the dog "learned" to salivate at the sound of the bell alone. Thus the dog produced a conditioned response to a conditioned stimulus. Thorndike[5] developed Pavlov's stimulus response ideas into a theory of learning by connectionism. Thorndike believed that learning could be explained by connections between stimuli and responses and developed three laws of learning, which have direct application to education. One of the major contributions of Thorndike was his discovery that the strengthening effect of a reward was much stronger than the weakening effect of punishment. This discovery was greatly expanded by Skinner[5], who formed a theory called operant conditioning.

Skinner's theory is rooted in behaviourism, as he believes that learning is explained as a change in behaviour as a result of a stimulus. Skinner developed this idea much further however, stating that the environment has a large impact on behaviour and with the concept of reinforcement. The implication of this for teaching is that learning is seen as a modification of behaviour: in order to teach, positive behaviour that we wish to instil in students is rewarded and any negative behaviour is punished. In this way eventually students will realise that "correct" behaviour results in rewards and so will carry out this behaviour more often. Consequently, operant conditioning advocates that once the conditioned response is given it is reinforced to ensure that the response is maintained or occurs more frequently.

Punishment is used to eliminate undesirable behaviours or responses. However, this must be managed carefully as it may be reinforcing unwanted behaviour, for example when a teacher reprimands a student and the students' peers cheer or laugh, they may be reinforcing the child's negative behaviour. As Thorndike and Skinner discovered, positive reinforcement is much stronger at shaping behaviour than punishment and so in this case, the child's behaviour is more likely to be reinforced rather than eliminated. However, Skinner's theory only advocates punishment when there are no alternatives and says that the positive reinforcement of the desired behaviour should be used in accordance with it. In this way, a desirable behaviour is taught to replace the negative one that is being reduced. Skinner's theory of operant conditioning has become the most accepted and used form of behaviourism today.

1.2.3. The behaviourist theory of learning and lecture

The behaviourist view of learning leads to teaching methodologies which are very much instructor centred and result in students being passive rather than active learners. Lecture relates to behaviourist theory in that instructors have set goals and behaviours that they want to elicit from their students. As a result teaching is centred on the instructor who breaks the material down and passes it onto the students. Desirable behaviour from the students is reinforced through good grades and undesirable behaviour is reprimanded. Research shows that lecture, although covering more content results in less long-term retention of information than PBL.[6] Consequently, students only gain a percentage of the knowledge that has been taught. As well as this, lecture does not account for all types of learning styles[7]: although it may suit some students to listen and take notes, others may need to be actively involved or need to see practical applications to learn effectively. As a result, lecture may result in students resorting to a "surface" learning approach; that is, they memorise facts or information but develop little or no understanding of what is being taught. This type of learning is further reinforced through traditional assessment methods, such as final examinations that only require superficial knowledge for the students to achieve high grades.

1.2.4. The constructivist theory of learning

The basic postulate of constructivist theory is that the student builds his or her own knowledge; learning does not come about from the student being told or presented with outside information. According to constructivist theory the student is an active participant in their own learning; they form their own understanding by experiencing and interacting with the world around them. Consequently, teaching methodologies based on constructivism must enable students to be actively involved in and develop their own methods of learning.

Problem Based Learning is based on the constructivist theory of learning, but it incorporates elements from many different theories that are related. The fact that PBL problems are real world based and involve students experiencing the process of solving them for themselves relates to the experiential learning theories of Dewey[8] and Kolb[7]. These theories view learning as taking place through experiencing the world around us and making sense of it. The group work aspect of PBL is related to social learning theories of Bandura[5] and Wegner[9] in that they see learning as a result of our social interaction with others. In contrast to the behaviourists' view, cognitivists seek to understand the internal thought procedures of the learning process rather than just the visible change in outward behaviour. The two theorists in this field who are most relevant to PBL are Piaget[10] and Vygotsky[11]. Although both these theories are constructivist based, Piaget takes a more cognitive view, whereas Vygotsky's outlook is social.

Piaget[10] believed that children learn through trying to incorporate their new experiences into their existing ways of thinking and knowledge. According to Piaget we learn by adapting, which occurs through assimilation and accommodation. Assimilation is the process of taking in new information; an example would be that water expands when it freezes. The next stage is accommodation, which involves fitting this new knowledge into existing cognitive structures. This will usually result in a change of these cognitive structures: in the example above, rather than now thinking that all substances contract when cooled, you alter this thinking to include the contradiction that was presented when you learned that water expands when freezing, unlike most other substances. These cognitive structures are connected in what Piaget called organisation. Thus it is important for students to develop a full understanding of new information in order to be able to organise it into their existing cognitive structures. This organisation along with adaptation results in schemata, which are organised patterns of thought and action that help people adapt to their environment. Thus when students experience something new they construct a new schema.

With cognitive constructivism and Piaget's work, social and cultural aspects do not play a vital role; it is the students' own construction of knowledge that leads to understanding. In social constructivist theories, however, these aspects are the key to the cognitive development of the person. The social constructivist theory that relates closest to PBL is that of Vygotsky. Vygotsky believed that culture contributes to children's cognitive development in two ways: it not only teaches them what to think, but also how to think. It provides them with knowledge as well as the process of thinking. For Vygotsky, cognitive development occurs through a dialectical process, whereby the child experiences something new, which results in cognitive conflict, the child then adapts its existing cognitive structures to incorporate this new information and thus develops. However, Vygotsky argued that it was through cultural and social interaction that this process took place. He believed that there was a certain region between what the child could do by him or herself and what they could do with help from others, in which learning could take place, which he called the Zone of Proximal Development. Thus in applying Vygotsky's theory the child should learn through solving problems with the help of others, usually that of the teacher, but it could also be that of peers. Vygotsky also believed that language is the primary tool through which children learn, so discussion with others is a vital aspect of learning.

1.2.5. The constructivist theory of learning and PBL

PBL fulfils the principles of cognitive constructivist education theory by enabling students to construct their own understanding by solving real world based problems. Each problem that the student experiences challenges them to discover new information, to make sense of this new information, to establish how it fits in with what they already know and to apply it. As well as requiring students to do all this it also necessitates that they construct their own understanding of the new information as they are not given the facts or an interpretation of it by anyone else and they have to make sense of it in order to apply it. Through solving the problems the students learn in essence how to learn, as they are guided but they are not given the answers. Students learn to build up their understanding through research and questioning what they already know. They use their previous knowledge to make sense of the new knowledge that they are presented with; they then apply their knowledge to finding a solution to the problem. They are going through Piaget's stages of adaptation and organisation in order to develop new schema, in other words to learn.

Problem Based Learning is also in many ways a very good example of Vygotskian theory being applied. Rather than students being presented with facts or being lectured to, they work together in groups. This group work aspect of PBL embodies Vygotskian ideas of cognitive development through social and cultural interaction. Students are presented with problems, which are challenging enough that they cannot complete them alone. Through working with others in their group, discussing ideas and explaining their thoughts they develop a solution to the problem. This is Vygotskian theory in action. The task of the instructor is to set the problems in such a way that all students are in their zone of proximal development. They are developing through social interaction; they are learning from one another, and discussion and language play an important role. Also, according to Vygotskian theory, the adult working with the student initially takes on most of the responsibility for guiding the problem solving, but this responsibility gradually transfers to the student. This is similar to facilitation in PBL, where at first when students are completely new to the process they do need a little extra guidance, with less and less being given as they progress. The one aspect in which PBL differs from this theory is that, rather than students interacting with a teacher or peers of higher ability, they are interacting with peers of the same ability, thus they construct their own understanding rather than gaining through social interaction with someone of more experience.

1.2.6. Resolving the differences between cognitive and social constructivism

As both Piaget's and Vygotsky's theories are constructivist based, they are fundamentally very similar. Both theories agree that students construct their knowledge through experience; the only aspect in which they differ is in how this knowledge is constructed. For Piaget, knowledge is constructed through a cognitive structure, for Vygotsky, it is through social interaction that the construction of knowledge takes place, however both recognise the relevance of one another's theories. During PBL students learn through social interaction, as well as through constructing knowledge, both processes are equally important; it is a methodology that has resulted from a merging of the theories of cognitive and social constructivism.

Piaget's basic beliefs were that cognitive development occurred through children constructing their own knowledge from experiencing the world around them. For Vygotsky it was through cultural and social interaction that children developed their thinking. Piaget also set down specific stages of cognitive development, whereas Vygotsky believed that cognitive development was happening from birth through to death and was too complex to be described in specific stages. However, these are the only real differences between Piaget's and Vygotsky's theories, and although for Piaget, the socio-cultural aspect wasn't so important, he still recognised the fact that it had a role to play:

" There is no longer any need to choose between the primacy of the social or that of the intellect: collective intellect is the social equilibrium resulting from the interplay of the

operations that enter into all cooperation" [12]

The same can be said of Vygotsky's thinking on the construction of knowledge: although he believed that understanding developed due to social interaction, he also believed that active construction of knowledge had its function.

"Activity and practice: these are the new concepts that have allowed us to consider the function of egocentric speech from a new perspective, to consider it in its completeness... But we have seen that where the child's egocentric speech is linked to his practical activity, where it is linked to his thinking, things really do operate on his mind and influence it. By the word things, we mean reality. However, what we have in mind is not reality as it is passively reflected in perception or abstractly cognized. We mean reality as it is encountered in practice" [13]

1.2.7. PBL versus lecture

As PBL and lecture are very different methodologies coming from contrasting learning theories, they result in different types of learning by students. Whether PBL or lecture is more suitable depends on the learning outcomes that are desired. The learning outcomes of lecturing usually include coverage of a broad amount of content material whereas PBL may result in less coverage of content.[14] However, lecture, although covering more content, results in less long-term retention of information than PBL.[15] PBL enables students to become responsible for their own learning and results in teamwork and life long learning skills that students do not develop from traditional lecture style courses. Traditionally there is very little group work, student centred or independent learning in lecture-based courses. PBL also results in increased student motivation; many studies carried out indicate that students are more motivated undertaking a PBL curriculum than a traditional one.[16, 17]

1.3. Overview of Problem Based Learning and its implementation

1.3.1. Introduction

PBL is an active learning process for the student. It is structured in such a way that the students construct their own knowledge by working with others to solve problems based on their own prior knowledge. The role of the lecturer or tutor in the learning process is that of a facilitator. Students determine what information they already have and what they need to learn, discover this information for themselves and then apply it to solving a real life problem. As a result of this process, PBL students develop critical thinking, life-long learning and teamwork skills. In essence PBL is a student centred learning method, which enables students to become responsible for their own learning [16,18,19]. This is in direct contrast to traditional lectures where the lecturer is responsible for student learning and which are content centred.

1.3.2. PBL models

As PBL has developed, a number of different ways of applying it have evolved. These PBL models are based on either how the facilitators are arranged or how the groups are arranged. When developing a PBL curriculum both a facilitator based and a group based model need to be chosen and used together. For example, the floating facilitator model may be used along with small group PBL. In this case the students would be in groups of four to six but there would only be one facilitator moving through the class. The type of PBL used will obviously depend on resources available as well as the size of the class. In essence PBL requires small groups and facilitators with most of the learning taking place through group discussion in order for the full benefits to be obtained.[20] However, with large numbers of students and limited resources small group PBL may not be possible. In this case large group PBL is a good compromise. Although it may not be as student centred as small group PBL, it has many advantages over lecture as a teaching methodology. Students taught through large group PBL retain the advantages that come from working through a problem driven curriculum, as a result their critical thinking skills and understanding of the concepts are more likely to develop. However, as they are in much larger groups those advantages associated with the group work may not be realised. In large groups there may be less of an openness to contribute from students, students may also find it easier to contribute less and so group work skills will not develop as well or maybe not at all in some cases.

The PBL model that we used in teaching the thermal physics module was "problem centred PBL"[21]. The Problem drives the learning process; through solving the Problem the students gain an understanding of the relevant principles and concepts. Students are provided with some information and anything else they need is readily available to them on the Internet or in textbooks. In grouping the students, we took the small group approach with students being placed into groups of four or five according to ability. As the module was to be delivered to three different class groups, students were also grouped according to their chosen subject. Two groups of first year Physics students; students studying Applied Physics (AP) and students studying Physics with Astronomy (PhA) and a second year class of students studying Science Education (SE) took the module.

In relation to students' knowledge of Physics, the Physics students and the Science Education students would be at similar levels. All of the Physics students had completed Leaving certificate Physics, although not all Science Education students would have. However the SE students had all completed the first year introductory course in general Physics, which would go beyond the scope of the Leaving Certificate. In addition to their Leaving Certificate, the Physics students would also have completed a lot of Physics modules during the first semester including the first part of the introductory general Physics course.

Overall there were four groups of AP students, three groups of four and one group of five, three groups of PhA students, one group of four and two groups of five, and finally three SE groups of five students each. In relation to the facilitators, the floating facilitator model was used, with four facilitators available for the ten groups, two facilitators being lecturers and two being postgraduate students. The reason we chose this model of PBL was because the whole course was to be delivered though PBL with no lectures or additional teaching aids, thus it was important that the were enough facilitators to guide the students, particularly at the beginning of the module when the method was new to them. The reason that small group PBL was chosen was in order to ensure that the learning was student centred and that the students would gain the benefit of group discussion. If larger groups were used it would be much easier for some students to not participate or lead the group in their own direction.

1.3.3. Group work in PBL

One thing that all types of PBL have in common is the fact that the students are split into groups in order to facilitate the learning process. The groups can either be mixed ability, that is, chosen to ensure that both high achieving and weaker students are placed into groups together. Or it can be arranged so that students of similar ability are grouped together[22]. As well as ability there are other considerations such as gender: the groups may be gender balanced or not.

In implementing PBL we grouped the students according to ability. The reason for this was twofold: it encourages peer tutoring and ensures that students were more likely to speak freely about their ideas; each student is in his/her proximal learning zone. It is important that students feel comfortable enough in the group to discuss possible solutions to the Problem, or ideas they may have about ways of approaching the Problem. If students feel able to speak freely about their understanding, all members of the group will have the opportunity to contribute to the discussion and so construct their own understanding of the concepts. Another aspect to students feeling free to participate in group discussions and admit their shortfalls is that it encourages peer tutoring. There were many examples during the tutorials of one person in a group explaining a particular concept to the others; this resulted in the members of the group gaining from each other's strengths. Another reason that it is important that students can speak freely within the group is to ensure smooth functioning of the group; students must be able to discuss any difficulties they are having interpersonally as well as academically. Arranging the groups according to ability, helped students to feel comfortable contributing to the Problem solving process, as they didn't feel that their ideas were inadequate or that their peers would think them unintelligent for displaying a lack of understanding.

Another reason why this type of grouping was chosen was so the Problems could be explored to different levels of complexity. We found that students of different abilities approached the problems from different perspectives. One example of this was noticeable when students went to solve part two of Problem One (see section 3.2.3). The students in the highest ability grouping, who were quite strong at maths, solved this problem by setting up a differential equation and solving it. Other students, whose mathematical skills were not as developed, solved it using other approaches such as graphing.

It was also decided that unlike some types of PBL, our students would not be assigned roles within the group. In some forms of PBL this is done and the students then change roles every week or so. However, we felt that this would cause students to be unsettled and to have to constantly adapt to a new role. Instead, as a result of not being assigned specific roles, students took on their natural roles in the group as the groups began to function smoothly.

Throughout the course of the PBL module, the placing of students within groups according to ability turned out to be advantageous. A number of Science Education students said that it brought them not only closer to their group mates but also brought the class together as a whole. It was also evident from observation that there was peer-tutoring occurring in many groups, and most groups functioned well. There were only two groups out of the ten that didn't function to the best of their ability and this was due to a lack of attendance and participation from some students (see section 2.3.3.) These students were penalised by receiving no marks for any group work in which they hadn't participated. This was discussed with all the group members and agreed on.

1.3.4. The benefits of PBL

The traditional approach to teaching at third level, namely lecturing, can result in "shallow" learning approaches by students. This type of learning is one that does not involve full understanding and retention of information; rather it results in low levels of comprehension and material being "reproduced" for examination purposes. As PBL is student centred and requires independent learning it can be very effective in combating this and promoting meaningful learning. [23] The main benefits of PBL are higher levels of comprehension and increased retention of information. The fact that PBL results in increased retention is documented in a study by K. Gabric and T. Ludovice

> "Long term effects on content retention, measured three years after the presentation of materials, indicate a significant improvement in content retention for those students who learned through PBL relative to those who learned more traditionally"[14]

Deeper understanding of subjects taught through PBL has also been reported; one example is that of Vernon and Blake who reported, "students in PBL programs place more emphasis on 'meaning' than on 'reproducing', and that the opposite pattern prevailed amongst students in traditional programs."[20]

PBL also results in the development of life long learning skills and social and group working skills. Walton and Matthews and many others assert that the PBL process encourages students to develop "self-directed life-long learning skills"[23] As well as this the co-operative learning involved in the process results in improved group work skills.[24,25] Finally, many of the studies carried out supported the fact that PBL improves motivation for staff and students. [15,17]

Through observation of the PBL tutorials it was clear that students were motivated, much more so than in a lecture based environment. Attendance averaged between 90 to 95%, which is much improved on lecture; attendance averaged between 60 to 70% for the same cohort of students in a lecture-based second semester module. As soon as students were given a Problem they began to discuss ideas and research into the concepts. It was evident from the reports that students had really thought about a lot of the physics concepts involved. The reports showed that PBL was successful in ensuring that students researched into the subject matter and thought about underlying principles behind the Problems. For most students this thought process and research resulted in a deeper comprehension of the material than they would have developed from lectures, for others this may not have been the case.

The problems were also complex enough that individual students would not be able to complete part or all of them alone, thus a "divide and conquer" method could not be employed by the students. This resulted in students gaining valuable experience of working with others. Even those groups that did not function as well as they could have improved students' group work abilities in that they had to cope with the problems and develop methods of dealing with them. In those groups that had difficulties the final examination results made clear those students that weren't contributing as they obtained significantly lower grades than those who did contribute fully to the problem solving.

In relation to students gaining life-long learning and independent working skills, as the module progressed research, and evaluation of this research, became more natural for the students. During the very first PBL tutorial not one person or group went to research the topic that the Problem was on, however by the last tutorial, every single group had nominated one or two people to conduct research on the given topic. These skills of researching and developing an understanding of a new topic should remain with students and hopefully be transferred to other aspects of their education.

1.3.5. Concerns in implementing PBL

Although PBL has many advantages, there are also some drawbacks to introducing the methodology. The main difficulty in developing and delivering a PBL based curriculum is the demand on staff time. In developing a lecture based course, a lot of staff time is required initially, however, once the course had been developed it doesn't require much additional time input. In contrast, a PBL module demands a lot of staff time. Firstly, more time is required in the development stages, as appropriate problems are difficult to create. The delivery of the module takes the same amount of time, however more than one staff member is needed as they are taking on the role of facilitators rather than lecturers and so there is a higher staff to student ratio. In addition to this, once the module has been delivered once, it is necessary to further adapt the problems on the basis of how effective they have been. There is also a lot of staff time taken up during the delivery of the module with assessment. One of the aspects of PBL is that feedback should be immediate; as such it is vital that students' reports are corrected and they are given recommendations as soon as possible. However, although PBL demands a lot of staff time, when implemented well, this input is rewarded by an increase in students' comprehension of the material and the development of their critical skills.

The argument could be made that increasing the staff to student ratio in a traditional lecture or tutorial setting should also result in improvements in students' learning; individual students would get more time to discuss difficulties or problem solving with lecturers. However, although this may increase students' ability to solve problems or answer questions it doesn't have to mean that they develop a deep understanding of the subject material or develop those skills attributed to a PBL curriculum.

PBL also places demands on resources. In order for students to be able to work together effectively it is necessary to have an appropriate environment. For our PBL module we had a dedicated classroom with a table for each group, whiteboards and a range of textbooks. There were also computers for each group available in the next room. It is essential that resources be provided for the students to enable them to carry out the research necessary to solve the problems. It is also important that students are comfortable in their environment and that they have a suitable place to hold group meetings outside class time so that they can work together to the best of their ability.

1.4. PBL and Physics Education

1.4.1. Why use PBL to teach physics?

PBL in physics is a relatively new development. PBL was originally designed in the 1970's for medical school curricula. [26] However PBL is becoming more and more widespread and is suited to any discipline and is, in fact, by its nature inter-disciplinary. PBL in physics can be very effective; it enables students to develop critical thinking and problem solving skills. It can also result in more in-depth understanding of physics concepts and an ability to apply physics to solve everyday problems.[27] One of the reasons that PBL is particularly useful in teaching physics is that it is very effective in developing physicists who are versatile, and possess modelling skills and the ability to think abstractly.

1.4.2. Examples of how PBL has been used to teach Physics

The University of Leicester has headed an initiative to promote Problem Based Learning in Astronomy and Physics, called project LEAP.[28] This project, co-ordinated by Dr. Derek Raine not only involved the development of PBL modules but also a campaign to increase the awareness of PBL in physics education. Project LEAP achieved this aim through running a number of programmes to help physics and astronomy teachers implement PBL, these included: summer schools on PBL, "road shows" and producing a guide to using PBL in physics education.

The type of PBL that project LEAP is involved in is small group PBL. Students are split into small groups of five to twelve usually and they develop their understanding of the material being delivered through solving real world problems. The emphasis of the projects findings is that in order to develop future scientists with the appropriate skills the way they are taught will have to be changed. This has lead to a completely new degree has being developed by Leicester University called i-science.[29] This degree is cross-curricular and doesn't have any stand-alone modules in single disciplines. It is delivered through Problem Based Learning rather than lecture. It is designed to ensure that students become skilled in: solving problems which require knowledge from a variety of different disciplines, working with others, independent research and applying their knowledge, which is what they will be expected to do when they graduate. In this way the degree is much more suited to developing scientists with the skills that they require for their careers than a traditional lecture based science course.

The University of Delaware have also used PBL in their science courses. They first introduced PBL in teaching their introductory Science courses ten years ago. Barbara Duch[1] is the Associate Director of the Mathematics and Science Resource Centre at the University and has implemented PBL in teaching her Honours General Physics course.[30] The class was split into groups of four students each and each student was assigned a specific role, (discussion leader, recorder, reported and focuser) with the roles rotating weekly. She was the only tutor and went from group to group aiding the problem solving process. As well as the group problems and group experiments there were also individual problems given to students. An independent consultant interviewed the students in order to evaluate their attitudes to the class and all responded that group work and problem solving helped their learning.

Another example of how PBL has been used in teaching undergraduate Physics is given by Douglas Kurtze, Department of Physics, North Dakota State University[27]. Kurtze attended workshops on implementing PBL in the university of Delaware and decided to implement it in teaching his introductory general Physics course.

Once again the students were split into groups of four, however there were two classroom assistants as well as the lecturer involved in order to facilitate the group work. There were mini lectures given occasionally after a problem when most of the students had difficulties with some aspect of it. After each problem the groups had to hand in a report explaining what they had done and why and what they had learned from solving the problem. The course was given in both academic semesters and there were improvements made for the second semester based on what had occurred during the first. More time was spent drawing out ideas from the groups at the beginning of the problems as it was found that one of the most difficult parts of the problem solving process was deciding what needed to be learned. As well as this it was found that students were having difficulty adjusting to working in groups. In order to combat this, quizzes were given which required the group to divide up work and then work together to learn it. Overall the findings in this paper show that the students' conceptual understanding of the physics rose significantly through PBL. The final comment being that although PBL is very effective it is important to donate a large amount of time ensuring the groups are functioning as they should be.

This method of implementing PBL was more similar to ours than that of Duch[1]. Like us, Kurtze[27] was applying PBL to one module in a lecture-based curriculum; he used small groups and a number of facilitators. In addition, Kurtze's method of assessment was similar to ours in that we also required students to hand in a report detailing how they solved each Problem.

In conclusion, the research on problem based learning shows that it can result in students who are able to apply their knowledge to solving real life problems, work effectively with others, and undertake self directed learning. Thus students who have studied physics through PBL are more likely to develop skills that allow them to function well in the workplace and use their knowledge of physics to good advantage. In comparison students that study through a traditional curriculum have little opportunity to use independent learning, group work and solve problems based on real life situations. Overall if the desirable learning outcomes include physicists that use their knowledge to solve real life problems, are life long learners and work effectively with others then PBL may be the answer.

1.4.3. Traditional approaches to teaching thermal physics

Thermodynamics has traditionally been taught from the macroscopic viewpoint, which is by looking at the directly observable properties as opposed to the molecular. However there are problems with this approach as it is rather abstract and so students may have difficulties in understanding concepts such as heat and entropy.[31] In order to help students visualise and develop a deeper understanding of thermodynamics a microscopic approach used in conjunction with the macroscopic may be of some benefit. Reif[31] suggests that a microscopic view offers the advantages of being, unified, modern, interesting and helpful towards students' further study. He also argues that the new concepts introduced in thermodynamics using macroscopic points of view are deficient in a "strong integrating framework" and the fundamental concepts such as absolute temperature and entropy remain difficult to understand. Lee[32] also advocates the microscopic approach stating succinctly "In an age when a single atom can be trapped and manipulated the teaching of thermal physics starting from the empirical laws of thermodynamics is a pedagogical scandal. It is now high time to reform the style of teaching thermal physics in introductory college physics courses."[32]

Both Reif and Lee have taught introductory thermodynamics from a microscopic approach and have reported positive results. Reif's method is based on the prerequisites that students should have some basic knowledge of classical mechanics and some mathematical knowledge about natural logs, derivatives and integrals. His approach is simple enough to teach to first year physics students once they have studied mechanics. Reif uses probability and the microscopic arrangement of atoms in order to yield all three of the classical laws of thermodynamics and how they can be used to make macroscopic inferences.

Lee's approach is based around a Java applet, which simulates the throwing of dice. The students need to understand the conservation of energy law and the principle of a priori probability before using the applet. The applet can then be used to help students understand the laws of thermodynamics as well as gaining a deeper understanding of entropy.

There may be a disadvantage to teaching introductory thermodynamics from a microscopic approach however. One study carried out on students understanding and reasoning in thermodynamics suggests that students have many misconceptions about the microscopic processes involved which lead to misunderstandings of laws and principles.[33] This study found that students misunderstandings of collisions in a simple microscopic model of a gas lead them to fail to recognise that it is necessary to examine the system's interactions with it surroundings to make judgements about heat transfer, work done and internal energy. Students' main misconception was that a change in internal energy is brought about by collisions internal to the system and this resulted in them failing to apply the First Law of Thermodynamics. Some of the students in this study also assumed an inappropriate relationship between volume and temperature as a result of underlying incorrect microscopic ideas; students made statements such as "The smaller volume forces the molecules of gas to increase in speed, therefore increasing the temperature" In order to eliminate incorrect macroscopic reasoning based on an incorrect microscopic model, this study suggests introducing microscopic models when students have become familiar with the macroscopic phenomena.

The research shows that whether a macroscopic or microscopic view is taken in the approach to teaching the key is ensuring that the students fully understand either the macroscopic phenomena before introducing microscopic models or vice versa. It is important to identify in advance the problems that the students may have, the concepts that they may find difficult and concentrate on ensuring that they fully understand them.

1.4.4. Why use PBL to teach thermal physics?

The research carried out on students understanding of thermodynamics[33,34,35] identifies that the main difficulties that students have are with differentiating between related concepts, such as heat and internal energy, understanding the concept of work in a thermodynamic context and recognizing the relevance of and applying the first law of thermodynamics and the ideal gas law. The suggestions put forward in order to help eliminate these problems include, approaching thermodynamics from a microscopic viewpoint, ensuring students have a full understanding of work in a mechanical context before introducing thermodynamics, and using tutorials and discussions to clarify concepts which students find difficult. From the findings, it can be concluded that in the teaching of thermodynamics it is important to distinguish clearly between related concepts, and to ensure that students have an understanding of the physical meaning of equations such as the first law and ideal gas law. This is important because, as discovered in these investigations, if students do not understand the physics behind equations they will have many difficulties in applying them. In essence the challenge of teaching introductory thermal physics lies in ensuring that students have a deep understanding of the concepts rather than a limited ability to apply formulae.

PBL is ideally suited to teaching thermal physics, as it can enable students to gain a deeper understanding of the concepts that they are studying through applying them. This will help ensure that students understand the fundamental principles of the physics and do not concentrate on applying formula alone. As the problems are real world based, they will help the students see the relevance of what they are studying and so will make it more meaningful, which will increase their motivation and retention. Finally the group work aspect of PBL encourages peer tutoring, which aids both the student who is tutoring and the students being tutored understanding of the topic.

1.5. Conclusion

Formal instruction begins with aims and objectives. The aims of the instruction are its overall purpose, while the objectives are more specific descriptions of intention. In order to achieve these aims and objectives a suitable teaching methodology must be employed. The aim of third level education is to provide students with a thorough knowledge of their chosen discipline as well as the skills required to work successfully in their field. In order to achieve this aim it is necessary to adapt teaching methods, as lecture has been found unsuccessful in most cases. If implemented properly, Problem Based Learning is an ideal methodology to develop students understanding and equip them with the necessary skills that they require. PBL is particularly effective for Science Education as it is more effective than lecture at developing essential skills such as, working with others, critical thinking and ability to research.

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Chapter Two Students' Attitudes to Problem Based Learning

2.1. Foreword to the Introductory Problem

As Problem Based Learning is a very different method of teaching to lecture, it is necessary that students are given some time to adjust. In developing a method of introducing the students to PBL we wanted something that would convince them of the benefits of making this transition and motivate them to approach the module with a positive outlook.

The first decision that we took was to refrain from lecturing students on the PBL methodology. We felt that this would be counterproductive as it is contrary to what the PBL methodology preaches. Rather than sitting passively listening to the benefits and possible difficulties with implementing PBL, the students benefit much more from experiencing the process for themselves by solving a problem. This led us to developing an introductory problem, which is shown below in Boxes 2.1 and 2.2. This Problem can be seen to fulfil of the requirements of the PBL methodology itself; it is open-ended, there is no right or wrong answer, it can be solved by all students, and it ensures students develop an understanding of PBL through experiencing it for themselves.

As one of the principles of PBL is that the problems should be "real world" based and relevant to the students it was necessary to make the Problem relevant to both the Physics and Science Education students (see section 1.3.2.). To ensure that the students saw the relevance of the Problem, we developed two different contexts. For the Science Education students, the Problem was based around introducing PBL into their own classrooms, for the Physics students, the context of the Problem was that they were researching into PBL, as they were going to be taking a module taught through PBL.

Thermal Physics Introductory Problem

Part One

During your teaching practice you discover that it just seems impossible to make certain lessons interesting to your students. You decide that it's time to try some other method, and think that perhaps things would be better if the students got actively involved in the teaching process.

You read up on the subject and get particularly interested in the area of Problem Based Learning in small groups. After a lot of humming and hawing you decide to give PBL a real go. How would you go about convincing your students that PBL can be a much more exciting way of learning science? What difficulties do you anticipate and how would you try to avoid these?

Part Two

You feel that assessing the groups is a potential minefield. For example, you don't want one person to dominate the group (either by dominating the discussions or by doing all the work) nor do you want any hangers-on (either by not participating fully or being continually late). What is your strategy to prevent this and what role can assessment play in this?

Box 2.1. *Introductory Problem of the PBL thermal physics module as given to Science Education students.*

Thermal Physics – Introductory Problem

Part One

As part of your first year studying physics you have taken part in a peer-tutoring programme and you feel that the group work involved was very beneficial to your learning. You discover that your class is going to be taking a module through Problem Based Learning (PBL) in small groups during the next semester.

Part Two

As you are talking with your classmates about the new PBL module you realise that although most of them feel that it will be beneficial, their main concern is with how the groups will be assessed.

Box 2.2. *Introductory paragraphs to the Introductory Problem of the PBL thermal physics module as given to Physics students.*

2.2. Students' response to the Introductory Problem

2.2.1. Comments on Part One

Part one of the Problem requires students to develop an argument supporting PBL as a teaching methodology. This was to ensure that students completed research into PBL and thought about the potential benefits of being taught through it, as well as examining evidence for and against the methodology. The second aspect to the question required students to think about the possible pitfalls in implementing PBL and how they might be avoided. In this way the question ensured that students gained a balanced view of the methodology.

One slight difficulty that we had with this Problem was that as the students had experienced some form of PBL before starting the module, they felt that they knew what it was and so didn't do as much research into the topic as we expected. Their opinions, however, were based on an experience of PBL that was very different from the one employed in developing and delivering the thermal physics module.

The Science Education students had completed a first year practical chemistry module through PBL. During this module students were given a problem to solve before the lab. In developing the solution to the Problem, students determined what work was necessary for them to complete during the laboratory. There were pre-lab sessions were the problems were discussed and students were forewarned of possible "blind alleys". It was necessary that all students develop a suitable method of solving the problem in the lab and so they had to be somewhat guided. Students were split by ability for some tasks and mixed for others and group size was also altered. In contrast, students were grouped according to ability for the thermal physics module, the groups remained fixed and the questions were open-ended.

The Physics students had experienced a methodology labelled PBL in a first semester module. However, once again it was very different to the methodology applied in the thermal physics module. Students were placed in groups, but were given the problems after instruction was complete. Consequently the methodology was more like traditional problem solving than PBL, as the problem did not drive the learning process. As a result of experiencing these modules, the students' felt that they knew what PBL was, which was not the case; in fact they had developed misconceptions and a negative attitude towards the methodology. Part One of the Introductory Problem went some way towards resolving these false impressions, but students did not complete as much research as we would have hoped, probably due to their prior experience.

Although Part One of the Introductory Problem was not fully successful in developing student understanding of the PBL methodology, it was a valid method of introducing them to the concepts involved. Students do not receive an introduction to note taking before they start a lecture-based course; this is in fact never addressed. However in PBL there is the opportunity to intervene early if students are having difficulties with the methodology or are not gaining the full benefits from it.

2.2.2. Comments on Part Two

Part two of the Problem focussed on the particular difficulties associated with group work and strategies to avoid these. This was because we anticipated that one of the difficulties that students may have in adjusting from lectures to PBL would be working with others. PBL makes students interdependent due to the nature of the group work. This part of the Problem was designed to ensure that students thought about what was involved in the group work aspect of PBL and also that they developed strategies to deal with any difficulties they may experience. In addition to this, it also enabled students to develop assessment schemes for the module that they thought were fair, in this way they realised for themselves why group marks as well as individual marks were necessary. See section 2.3.3 for a discussion of students' answers to this part of the Problem.

2.2.3. Conclusion

From observing students during tutorials it was evident that the Introductory Problem succeeded in making the students complete research, develop their ideas and become involved in group discussions. Students experienced the advantages as well as some of the difficulties involved in the PBL methodology for themselves. They also began to develop their group work skills, with many students gaining an insight into the personalities, strengths and weaknesses of other students in their group and determining the best method of working together.

2.3. Students' attitudes to PBL before the module

Students answers gave us an insight into their attitudes towards PBL before the module began. In students' answers to the Problem, three main categories emerged, the advantages and disadvantages of PBL and strategies to overcome any difficulties that may be encountered in implementing PBL.

2.3.1. Students' opinions of the possible advantages of PBL

It was clear from students' answers to the Introductory Problem that they didn't consider that PBL would improve the quality of their learning (see Table 2.1. below), with only one of the ten groups saying that it results in better understanding of what is being taught and two saying that it results in better retention of the knowledge, but they didn't give references. In general the students seemed to be more concerned with grades and results than with understanding or the amount of material covered, which is illustrated by the fact that while no groups mentioned the better understanding as an advantage, nobody mentioned that a disadvantage of PBL could be that less content material is covered either. Rather than concentrating on the academic advantages of PBL as a methodology they focused on the advantages of the group work involved, with seven of the groups saying that PBL would improve their ability to work with others and five saying it would result in better motivation.

Three of the seven Physics groups remarked that PBL would result in them developing skills useful for their future careers whereas none of the Science Education students did. We think this may be a result of the Physics students viewing teamwork as being an integral part of their careers, while the Science Education students may view it as less relevant. Science Education students tended to focus more on the educational benefits of PBL, mentioning things such as, it is a change from the usual methodologies, all three of the groups stating this with only one physics group mentioning it. Science Education students also mentioned things such as student-centred and self-directed as well as the benefits of PBL for mixed ability whereas Physics students were less likely to look at it from an educational perspective.

Comments	Total	Physics	SE
Student centred	4 /10	2/7	2/3
Students are active rather than passive	1/10	1/7	0/3
Own goals rather than instructors	3 /10	1/7	2/3
Learning by overcoming difficulties	1 /10	1/7	0/3
Solving the problem drives the learning	2 /10	2/7	0/3
Feedback is immediate	1 /10	1/7	0/3
Change from usual methodologies	4 /10	1/7	3/3
Better motivation	5 /10	4/7	1/3
Better retention of knowledge	2 /10	1/7	1/3
Improves critical thinking skills	4 /10	2/7	2/3
Improves problem solving skills	3 /10	2/7	1/3
Improves group work skills	7 /10	4/7	3/3
Good for mixed abilities	3 /10	1/7	2/3
Good preparation for employment	3 /10	3/7	0/3
Results in better understanding	1 /10	0/7	1/3
Instils life-long learning skills	1 /10	1/7	0/3

Table 2.1. *Advantages of PBL as listed by groups of students in answering the Introductory Problem.*

2.3.2. Students' attitudes to the possible disadvantages of PBL

Once again students concentrated on the group work aspect of the methodology with most of the disadvantages listed being related to this area. Although Part Two of the Introductory Problem specifically concentrated on the difficulties associated with group work, students were asked to list the possible problems in Part One of the Problem. Consequently, the fact that students concentrated on these difficulties demonstrates that this was the area of the PBL methodology that they were most worried about. This is also evident from the number of groups that discussed these difficulties (see table 2.2. below), with nine out of ten of them saying that lack of participation in the group could be a serious problem and seven out of ten expressing concern over domination of the group by one member. Half of the groups also mentioned differences of opinion as well as conflicting personalities as things that would have to be dealt with in order for a group to function properly.

Surprisingly, only one group mentioned the fact that student concerns over change and grading would be an issue in adapting to a PBL environment. No students mentioned possible academic difficulties such as there being less content covered in comparison to lecture. As with the advantages, this indicates that students concerns are based around the impact of a new methodology on their workload, grades and interpersonal relationships with their classmates.

Comments	Total	Physics	SE
Lack of student participation in the group	9/10	6/7	3/3
Differences of opinion between group members	6/10	5/7	1/3
Student not using time efficiently	1/10	0/7	1/3
May not be suitable to use with practical work	1/10	0/7	1/3
Time restrictions	2/10	0/7	2/3
Problems with different levels of ability	5/10	4/7	1/3
Domination of group by one member	7/10	5/7	2/3
Division of tasks resulting in less learning	1/10	1/7	0/3
Conflicting personalities	6/10	6/7	0/3
Lack of resources	1/10	0/7	1/3
Student goals mismatched with instructors	3/10	1/7	2/3
Student concerns over change and grading	1/10	1/7	0/3
Problems with coordinating group meetings	2/10	2/7	0/3
Problems with lack of motivation	1/10	1/7	0/3

Table 2.2. *Disadvantages of PBL as listed by groups of students in answering the Introductory Problem.*

2.3.3. *Strategies developed by students to overcome potential difficulties*

In developing methods of overcoming potential difficulties, Physics students concentrated more on effective ways of ensuring smooth group work by working on interpersonal skills, whereas Science Education and Physics with Astronomy students concentrated more on assessment methods. One group out of the ten stated that the module should be just group marked and another that it should be individually marked. Four out of the ten groups said both group and individual marks should be awarded which is similar to the actual assessment scheme, in which all assignments are grouped marked and the final exam is individually marked with both contributing equally to the students overall grade. The students' reasoning behind the marking scheme was that: a group mark may reward people who have not put in the work and be unfair to those who have worked diligently. On the other hand group work is an integral part of PBL and so should be assessed, this is why they thought that it would be most fair for both a group and an individual mark to be awarded.

Half of the groups also thought that attendance should be made compulsory, or that it should be marked. However, during the discussion the class decided as a whole that they would keep track of their own group members' attendance. If there were any problems with one or more group members' attendance they would try to deal with it themselves as a group first, then if there were still significant difficulties they would ask a facilitator for guidance.

Comments	Total	Physics	SE
Be aware of possible group problems and discuss	3/10	3/7	0/3
Ensure all members are comfortable to speak	1/10	1/7	0/3
Support and encourage group members	2/10	2/7	0/3
Encourage respect and compromise	3/10	3/7	0/3
Make attendance compulsory	5/10	3/7	2/3
Mark attendance	5/10	3/7	2/3
Award group and individual marks	4/10	2/7	2/3
Only award group mark	1/10	1/7	0/3
Only award individual mark	1/10	0/7	1/3
Have continuous assessment assignments	1/10	1/7	0/3
Assign roles and rotate them	2/10	1/7	1/3
Monitor progress by observation and questioning	3/10	1/7	2/3
Divide task up amongst group members	5/10	4/7	1/3
Ensure resources readily available	1/10	1/7	0/3
Provide clear learning outcomes	1/10	1/7	0/3

Table 2.3. *Strategies developed by groups of students in answering the Introductory Problem to overcome possible difficulties in implementing PBL.*

2.4. Students' attitudes to PBL after they had completed the module

2.4.1. Introduction

We decided that in order to assess the impact of the PBL module on students' attitudes to the methodology we would develop a questionnaire to be given when students had completed the module. The reasons that we chose a questionnaire format were:

- It could be completed by students in a relatively short amount of time and so could be given in the last tutorial without affecting the time students had for completing the final Problem

- As it was anonymous, students may be more likely to express their true feelings, in contrast to orally questioning students, where the interviewer may influence them
- As it was based on a rating scale, it enabled us to gain some quantitative information about the effect of the PBL module on students' attitudes

2.4.2. Students' opinions on adapting from lecture to PBL

This was a very short section of the questionnaire designed to obtain quantitative data on whether students found it difficult to adapt to the PBL methodology. 77% of students agreed or strongly agreed that changing to PBL involved role changes for both themselves and lecturers. In relation to whether or not the change was difficult, the students were almost equally split with 39% agreeing that it was difficult and 42% disagreeing, 19% weren't sure. Students were split equally about being concerned over grading, 33% agreeing, disagreeing and undecided. It is evident from these results that most students did see PBL as involving them and the teaching staff adapting. It was encouraging to see that most students didn't find the change too difficult, however, as the results are so closely split it most likely indicates that every student found it challenging to some degree.

2.4.3. Students' attitudes to the advantages of PBL

This section of the questionnaire was designed so that it could be compared to students' attitudes to PBL before the module. It consists of ten statements (see Table 2.4. below) and of these there were eight that more than 50% of students agreed with. This is an overall positive result. The two statements that less than half the students agreed with involved long-term benefits, 39% and 36% of students respectively stated that they neither agreed nor disagreed that they had obtained these benefits from PBL. This may well indicate that students were unsure if they had benefited in this way as it was too soon after the module to know.

Statements	Agree	Disagree	Neither
Ensured that I was active rather than passive	**65%**	16%	19%
Was good because feedback was immediate	**65%**	10%	26%
Improved my critical thinking skills	**68%**	10%	23%
Improved my problem solving skills	**74%**	10%	16%
Improved my group work skills	**65%**	10%	26%
Instilled life-long learning skills in me	35%	26%	39%
Was good preparation for my future employment	**61%**	6%	32%
Resulted in me having better understanding than I would have with a lecture based course	**52%**	32%	16%
Resulted in me being more motivated than I am in lecture based courses	**58%**	23%	19%
Resulted in me retaining more knowledge than lecture based courses do	35%	35%	29%

Table 2.4. *Results of questionnaire on students' opinions of the advantages of PBL.*

In comparing these figures to students' attitudes before completing the module (Table 2.1.) it can be seen that it has had a positive affect on students. Only one group out of ten mentioned that being active rather than passive was a benefit of PBL and after completing the module, 65% of students agreed that PBL had ensured that they were active rather than passive. Students appreciation that PBL results in the development of additional skills was also evident after the module, with 68% and 74% agreeing that the module resulted in them having improved critical thinking and problem solving skills respectively.

2.4.4. Students' attitudes to the disadvantages of PBL

The part of the questionnaire that related to the disadvantages of PBL contained nine statements (see Table 2.5. below), which were related to those concerns that the students had expressed in answering the Introductory Problem. The results of this part of the questionnaire were less positive than those to the section on advantages. There were only three out of the nine disadvantages listed that students disagreed with. Students didn't feel that lack of resources, conflicting personalities or domination of their group by one member were disadvantages during the module. There is evidence that completing the module had a positive effect on students' attitudes towards these aspects of PBL, as after completing the number of students that felt that these were disadvantages dropped by 44% and 41% respectively.

Those disadvantages that were agreed with by more than half the students were: that it was difficult to co-ordinate meetings outside class time, that the course required more time than a lecture based one and that they missed out on some aspects of the Problems. In relation to the meeting outside of class time, we were aware that this can be difficult and only formed groups of students from the same class group in order to make this process easier. From observing the students during the module it was evident that most did manage to meet outside of the class time and 40% of students indicated that they didn't have any difficulty with this.

58% of students said that the course required more of their time than a lecture based one would. However, they had the same number of contact hours as a lecture based module (36 hours) and we developed the Problems so they could be solved within the set number of hours that students would be expected to spend on independent work for a lecture based module (36 hours). Students usually do not spend this independent study time during the semester and complete all the work just before the exam. As students had to spend time solving the Problems and sit a written exam, they felt it required more work than a lecture-based module. Although some students spent more time on certain Problems than was allocated, most groups solved the Problems within the contact and independent study time allocated and so didn't spend longer than they would have done for a lecture based course.

52% of students said that they agreed that they missed out on some aspects of the Problems because the work was divided up amongst members of their group. The reason that we included this question was because we felt that some of the groups might be trying to employ this strategy to solve the Problems. Most of the Problems were too difficult to solve without the help of other members in the group, however some groups had a group discussion about the general approach and then divided up the work, which meant that students missed out on the specifics of some parts of the Problems. Students were encouraged to solve the Problems together, the fact that they had to sit a final individual exam also helped ensure that they made sure to understand all aspects of the Problems. Not all groups tried to take the "divide and conquer" method, many did solve the Problems together, however students missing out on aspects of the module is a serious concern. In order to ensure that all students attempt to develop an understanding of the concepts and principles behind all parts of the Problems the Introductory Problem will be adapted for the next delivery of the module. As the difficulty is related to the group work aspect of the module, it will fit in with part two of the Introductory Problem; students will be asked to develop strategies to ensure that every aspect of the Problems are covered and that all members of the groups understand everything. This will ensure that students have thought about the necessity of covering all parts of the course before beginning and should reduce the number of students missing out on aspects of the Problems.

Statements	Agree	Disagree	Neither
Was lack of resources	16%	**68%**	16%
Was domination of my group by one or two members	29%	**55%**	16%
Was trying to coordinate group meetings outside class time	61%	23%	16%
Was that my goals were mismatched with those of the instructors	16%	39%	45%
Was having to cope with different levels of ability within the group	39%	32%	29%
Was lack of participation in group work by some members of my group	32%	48%	19%
Was that it required more of my time than a lecture based course would	58%	23%	19%
Was that I missed out on some aspects of the problems	52%	32%	16%
Was conflict between my group members resulting from differences of opinion	16%	**71%**	13%

Table 2.5. *Results of questionnaire on students' opinions of the disadvantages to PBL.*

Completing the module resulted in students developing more positive attitudes to the group work aspect of PBL; this can be seen in the decreased number of students being concerned about dealing with different personalities within their group. In addition to this, one of the students' main concerns before completing the module was that there would be a lack of participation in the work by some of the group members, with 90% of groups expressing concern over this. However, after completing the module, only 32% of students agreed that lack of participation by some members of the group was a disadvantage of PBL. Overall the students' responses to this part of the questionnaire are positive. Although there are a number of disadvantages evident, the number of students agreeing that they caused difficulties is relatively low.

2.4.5. Students' general opinions of PBL

The final part of the questionnaire provided students with statements relating to peer tutoring and the assessment of the module (see Table 2.6 below). Although students' main concern before completing the module was achieving effective group work, it can be seen from the results of the questionnaire that overall the group work was seen as a positive aspect of the module. More than half the students said that they learned a lot from others in their group and also found it helpful explaining concepts to other students. This is in contrast to the amount of students that said that peer tutoring occurred in their group. However, only 19% said that peer tutoring didn't occur, most said it did or did not know. This indicates that students may not have been aware of what the phrase means, since they answered the other questions in relation to group work positively. The fact that the group work was successful is also evidence by the fact that over 70% of the students said that they worked together with their group members to solve the Problems. This is also reflected in relation to the assessment of the module, as 87% of students agreed that it was fair that both group and individual marks were awarded.

One of the difficulties that we had during the module was achieving one hundred percent attendance. This same difficulty is experienced in lecture-based instruction. However due to the group work nature of PBL, absenteeism presents more of problem for PBL. Although attendance during the module was typically between 80-95%, there were difficulties, as the absenteeism problems were with specific students and so it was always the same groups that were at a disadvantage. In all of these groups there was one student who was constantly absent. In one group, one member didn't participate at all in the last three Problems; in two others one member didn't participate in the last two Problems. When facilitators first observed that there were members of some groups constantly absent, it was discussed with the other members and they were asked if they wanted the facilitator to speak with the student in question. Both groups declined and said that they would rather talk to the student in question themselves, which they did. However when this failed to have any effect on the students attendance, one of the facilitators, talked to the students that were absent to see if there was a reason for it. It turned out that one student had a negative attitude toward the module and felt that it wasn't his responsibility to have to attend tutorials. Another student was apathetic to his whole degree course, and was absent from many other modules. The third student that was constantly absent or not participating was also absent from many other modules and was happy to let others do the work for him. The importance of attending tutorials, particularly in relation to sharing responsibility for the work with the other group members and the relevance of the material to the final exam was discussed with these students. This had some effect on two out of the three students, increasing their attendance. Towards the end of the module, it was evident that the other members of the groups in question felt that it was unfair that students who had not participated at all were receiving the same marks for the Problem reports. All of the facilitators agreed with this and we decided that in order to take into account the lack of participation by group members, they would receive no marks for reports that they had no input into. This strategy was discussed with the groups and they were given the responsibility of determining the reports that the absent members had not participated in. Attendance itself was not assessed, as students were not awarded marks for attending and were not penalised for absenteeism but rather for regular lack of participation. However, awarding marks for attendance may go someway to ensuring student participation, so in order to assess students opinions we included a question on grading attendance on the questionnaire. 71% of students agreed that attendance should form part of the assessment of the PBL module.

Finally, there were two questions that assessed students overall opinions of the PBL module. The results of these questions were overall on the positive. 45% of students felt that it was an advantage having the module through PBL, and only 16% disagreed with this statement. In relation to having other modules through PBL, it was equally split between agreement, disagreement and undecided. As this questionnaire was carried out straight after the module was completed, the students will not have seen some of the long-term benefits of it; for example, they had not yet had their final exam.

Statements	Agree	Disagree	Neither
A lot of peer tutoring occurred within my group	42%	19%	39%
I learned a lot from others in my group.	65%	19%	16%
I found it helpful explaining concepts to others in my group	58%	23%	19%
Our group solved the problems together most of the time	74%	13%	13%
I think it was an advantage having this module through PBL	45%	16%	39%
I think its fair that both group and individual marks are awarded	87%	0%	13%
Attendance at PBL tutorial should be part of the assessment	71%	13%	16%
I would like to have other modules through PBL	35%	32%	32%

Table 2.6. *Results of questionnaire on students' opinions of the disadvantages to PBL after they had completed the module.*

2.5 Conclusion

Before starting the module students main concerns about changing from lecture to PBL were centred on the group work aspect of the methodology. There was very little evidence of concern over academic aspect of the module, such as the amount of material covered or how students were going to be graded. This was also evident in relation to the positive aspects of PBL, with few students mentioning benefits such as increased comprehension and most students focussing on the improvement in interpersonal skills. Through completing the module, students had to deal with those difficulties that they foresaw, such as conflicting personalities within groups and through this they developed new skills and abilities. Students' appreciation of this was evident in their response to the questionnaire, with very positive responses indicating that they gained a lot of skills through completing the module. Although the group work aspect of the module was still seen as the aspect causing the most difficulty even after it was completed, students were less concerned about certain aspects of it, such as lack of participation, as they had experienced them and learned to deal with them. Overall completing the module had a positive effect on the students' attitudes to and opinions of PBL, particularly in relation to group work.

Chapter Three Discussion of Problem One

3.1. Introduction to Problem One

We decided that the first Physics problem, which is presented below in Box 3.1, should deal with heat transfer as it relates to students' everyday experiences and contains some of the basics of thermal Physics. Van Kampen *et al* report on the implementation of this Problem during the first delivery of the module[1]. All parts of the problem in its initial form achieved the learning outcomes, except part two. Consequently, we only changed this part of the Problem for the second delivery of the module.

Thermal Physics – Problem One

Part One

Bob and Martha are physicists who live in a house that was built in the 1960s. The house has a central heating system and is generally in good condition, but there is no form of insulation in the house.

On a cold winter's day, the heating system breaks down suddenly. While they're waiting for the plumbers to arrive, they monitor the temperature in the living room. What factors determine how quickly the temperature will decrease?

Part Two

With the heating system no longer functional the temperature in the house is dropping substantially, Bob notes that it has dropped by 4°C after the first hour and he is getting worried about his goldfish. On the one hand he doesn't want to leave Martha on her own in the house, on the other hand he knows once it gets too cold the goldfish will probably die. How long does he have before he has to leave the house with the goldfish to save it?

Part Three

The plumbers arrive in time and get the heating system going in no time. With his goldfish swimming happily in their bowl, Bob and Martha now realise that this episode has given them a good if unwanted opportunity to see if insulating the house is economically viable. After estimating the surface area of their house they estimate its overall thermal transmittance.

To see what kind of insulation they need most, they consider two options: insulating the walls and roof with Styrofoam or replacing the windows with double-glazing. After a bit of research they collect some data that is tabulated below. They probably don't have enough money in the bank to pursue both options at once. Through a friend they know that can get either at roughly the same price. Their decision will therefore be based on how much they save on the heating bill. Which option should they go for?

Part Four

There is a grandfather clock in the living room of the house. After a couple of weeks they notice that the clock is running slow. Bob and Martha suspect this is because the room is hotter than before they insulated the house. Carry out calculations to check if this is a likely cause.

Could the pendulum be used as a thermometer?

Box 3.1. *Problem One of the PBL thermal physics module.*

3.2. Students' response to Problem One

3.2.1. Comments on Part One

As can be seen from the wording of the problem, it is very much "real-world" and something that the students could think about through experience, without any recourse to a formal knowledge of thermal physics. This meant that all members of the group had something to contribute to the discussion of the physics and so the development of communication and interpersonal relationships within the newly formed groups was encouraged. As well as this it establishes the method of considering the physics before applying formulae, as no calculations are required, which is a new way of thinking for most students.

From observing students during their first PBL tutorial when they were given this problem, it was clear that they were motivated to solve it: group discussion started immediately and it was reassuring for students to be able to go about answering the first part of the problem right away. I deduced this from observation notes that I wrote immediately after class. As the students were unaware of this, the observations did not affect the students' behaviour. Students' reports showed these observations to be correct. All groups had successfully answered the problem and shown signs of thorough thought. Nine out of the ten groups had considered factors relating to all three methods of heat transfer (conduction, convection and radiation) and only two of the groups included formulae in their answers. As well as developing understanding of the thermal physics concepts, such as heat transfer, this part of the Problem also instilled confidence in the students as they found that they could begin to develop an answer immediately.

A representative student answer to this part of the Problem is shown below in Box 3.2. It can be seen from this answer that part one of the Problem was successful in enabling these students to think about the methods of heat transfer. They have also thought about the affect of thermal transmittance but have failed to explain exactly what this is, this was pointed out to them with a comment on the report, as can be seen. Also, these students have listed examples of forced convection in their answer, most likely without realising that this was the case, as they have entitled them examples of convection. This was also pointed out in feedback to the students by means of a comment, in this way it was hoped that the students would revise their report and research further into the topics involved, for example, looking at the differences between forced and natural convection. Only one out of the ten groups failed to consider factors relating to all three types of heat transfer, mentioning conduction alone.

We determined that heat flow out of the house depends on

Conduction:

- The difference in temperature between the internal side of the wall and the external side.
- The U-value of the wall itself, if it has a higher U-value then there will be a higher heat flow through it, and similarly a low U-value will mean a lower heat flow. *what's that?*
- The area of walls/ roof that the heat has to flow through.
- How thick the walls are. If the walls are thin, ~~than~~ *then* there will be more heat loss through it than through a thick wall.
- Is the house detached or semi-detached? If there is a wall linking two houses then the heat flow through that wall will be minimal because the temperature difference between those two walls would be so small.
- The amount of windows that there are in the house. Plus are the windows single glazed or double-glazed? Double-glazing would reduce the heat flow through the windows.
- The décor of the house could affect the rate of which the temperature would drop. If there are ten layers of wallpaper on the wall then that would have to ~~an~~ affect ~~on~~ the thermal conductivity through the wall. If the house consists of stainless steel décor then the house would cool much quicker.

Convection:

Convection currents could be caused in the house by;

- Any open windows in the house causing a draft through the house.
- A ~~W~~indy day. If the wind outside was blowing wildly then there would be more draughts and hence the house would cool quicker.
- Other draughts, which may not be noticeable, e.g. draughts under doors.

example of forced convection

Radiation

Radiation doesn't play a major role in the heat loss of the house but there is a small factor, which, would contribute to the heat loss.

- Colour of the house. If the house were white ~~than~~ *then* it would lose its heat quicker than a house that was black.

Box 3.2. *Representative student answer to Part One of Problem One of the PBL thermal Physics module.*

3.2.2. Comments on Part Two

The original version of Part Two, shown below in Box 3.3, did not achieve all of the learning outcomes.

Part Two (Original)
When the heating system gave up the ghost, Bob and Martha's detached two-story brick house was a cosy 22 °C, while the outside temperature was 5 °C. They measure that after only an hour the temperature has dropped to 18 °C. Bob is getting really worried about his beloved goldfish. On the one hand, he doesn't want to leave Martha on her own in the house; on the other hand, he knows that once the temperature drops below 12 ° C, the goldfish will probably die. How long does he have before the situation becomes critical?

Box 3.3. *Original version of Part Two, Problem One of the PBL thermal physics module.*

This question was designed to encourage students to think about the relationship between heat loss and temperature as a function of time. An approximate graphical solution to the Problem would have sufficed, as students would be gaining an understanding of this relationship; but the students would be guided towards setting up a differential equation. It was necessary to provide the data so that they could solve the Problem.

However, what happened was that all of the groups discovered Newton's Law of Cooling and its solution

$$\Delta T = \Delta T_0 e^{-\alpha t} \qquad (1)$$

and applied it by substituting in the figures. This meant that the students solved the Problem without developing any understanding of the physics behind Newton's Law of Cooling.

When this difficulty was analysed it became clear that the way that the question was written didn't correspond with the learning objectives. The original problem is similar to a typical end of the book problem, albeit set in context.

Even though the students discovered Newton's Law of Cooling, those in the weaker group still found it difficult to obtain a numerical answer. These students were guided by facilitators to develop a mathematical strategy to deal with these kinds of problems, as well as to discuss the drop in temperature inside the house as a function of time. The students in the groups with stronger mathematical ability were encouraged to develop an expression for the relationship between heat flow and temperature by combining the equation relating heat and temperature change

$$Q = mc\Delta T \tag{2}$$

and the equation for heat flow by conduction:

$$\frac{dQ}{dt} = \frac{kA\Delta T}{d} \tag{3}$$

Once the students understood the physics behind both of these equations and that they related heat flow and temperature mathematically, they were told that equations 2 and 3 could be solved to yield equation 1. Students that are more mathematically advanced might be able to set up and solve the differential equation themselves.

To avoid students approaching the Problem without thinking about the physics involved again, we reformulated the question, as shown above in Box 3.1. The new version of the question requires students to estimate an inside and outside temperature, as well as to research into the temperature below which goldfish die. This addition instilled confidence in insecure students, making them feel they could make a valid contribution to the problem solving process by carrying out the relevant research. In addition to this, it makes Newton's Law of Cooling a less obvious choice. The revised problem proved to be successful. Most groups started by thinking about heat flow through conduction and the thermal conductivity formula. However, they soon discovered that they couldn't use this formula yet due to lack of information. Many groups asked the question of whether they could just assume a 4°C drop in temperature every hour. They were then encouraged to develop an answer for themselves through questioning from the facilitators. For example, when one of the SE groups was attempting to solve the problem, they were discussing among themselves if it was expectable to assume a linear drop in temperature. Three of the students in the group were unhappy with this as they were arguing that from experience and thinking about the factors involved in the heat loss, the drop in temperature inside the house with respect to time couldn't be linear. However the other students were saying that as they didn't have enough information they had to make an approximation. This in turn brought up the difficulty of determining what approximations were valid and which weren't. One of the students then asked a facilitator if they could assume that the drop in temperature was 4°C each hour after the heating was turned off. The group were then asked by the facilitator what the temperature of the house would be in two days if this were the case, they thought about this and realised that it would be an unreasonable value. This led them to consider why the temperature doesn't keep dropping and they realised that the temperature would stop dropping when it reached equilibrium with the outside temperature. Through this they developed an understanding that the relationship between temperature and time is not linear.

However, if students were to look back, it turns out that a linear approximation would have given students nearly the same answer – just under four hours, as that calculated using an exponential model. It is important that students do not develop the idea that they adopted a more difficult mathematical model for no reason. Firstly, all students assumed a linear model with no justification; none looked at the Problem and said "the numbers work out so that the cooling, while exponential in principle, can be approximated as a linear process". Secondly, there is value in verifying afterwards by how much the times calculated in each model differ.

As well as requiring students to think about the physics involved and the relationship between heat loss and temperature over time, the problem also obliged students to start to make assumptions, estimations and approximations. Students found this difficult at first, especially some of the higher ability groups, which were having trouble simplifying the problem. This was the also the case during the first delivery of the module. A discussion with a student having difficulty with making valid assumptions about part two of the Problem taken from observation notes is given below in Box 3.5.

One student from the group asked "how simple do you want this to be, you could just assume a four degree drop every hour" he then went on to say that this isn't a very accurate description of the rate of cooling, but that if you took into account everything involved such as thermal conductivities of different materials, convection, and the amount of exposure to sunlight then the problem would become unsolvable. Once the student was asked if his assumption about the temperature drop was a valid one, he immediately said no. When asked if exposure to sunlight was going to play a large factor in the heat loss, he said that it wouldn't and so he realised that it would be a valid assumption to say that heat from sunlight was negligible in the calculation. In this way the student realised that he had answered his own question and that the difficulty of the problem would depend on how many valid assumptions and simplifications could be made. In general it was very encouraging to see that all of the groups were beginning to make assumptions and estimations and question them, even if they were not aware that they were doing so.

Box 3.5. *Report on discussions with students about the modelling process that took place during a PBL tutorial.*

3.2.3. Students' answers to Part Two

It was evident from students' reports on the Problem that it succeeded in developing their understanding of the relationship between heat flow and temperature as a function of time; see Box 3.6 below. In addition to this, the Problem also resulted in students beginning to develop modelling skills, see Box 3.7 below. It is evident from these students' response that they were required to make valid assumptions and estimations in order to answer the Problem. Both these groups of students went on to integrate Newton's Law of Cooling and used it to determine how long it would take to reach the temperature at which the goldfish would die. Eight out of the ten groups solved the Problem in this way; the remaining two used a graphical approximation.

Instead we took a different approach to the question, we were told that the temperature dropped by 4°C in an hour. We then realised that as the temperature inside the house decreased it would become closer to the temperature outside. Therefore the rate at which the heat will flow through the wall would decrease. It would decrease by a constant rate. Why? What exactly do you mean by this?
In thermal physics, Newton's law of cooling explains this. *Newton's Law of Cooling states that the rate of change of the temperature of an object is proportional to the difference between its own temperature and the ambient temperature (the temperature of its surroundings)*

Box 3.6. *Representative section of students' answer to Part Two, Problem One of the PBL thermal physics module.*

It is evident from the students answer in Box 3.6 above that they have developed an understanding of the relationship between temperature and heat loss as a function of time. However, they don't explain what they mean by constant rate or why the heat flow will decrease at a constant rate. This was pointed out to them when they were given feedback on their report.

The students' answer to part two below in Box 3.7, demonstrates that students have begun to develop many of the critical skills that PBL encourages. The fact that students state that they started off with a very complex model in which they were going to consider body heat and the specific heat capacities of the water in the fish bowl compared to that of air but then realise that a these factors are negligible demonstrates that they are developing modelling skills. However, students do say that they are "only" working with assumptions and guesses. This contradicts what they have said about certain factors being negligible as this involved careful consideration of the Physics, not just guesswork. It may indicate that although students have started to develop modelling skills, they do not realise this or fully appreciate what the value of what they are doing.

It is also encouraging to see the students saying that the specific heat capacity and thermal conductivity formulae, which they were most familiar with, only resulted in them gaining random pieces of information, as this is what we expected students to find. The fact that students attempted to use these equations first is evidence that the change made to the Problem was successful in making Newton's Law of Cooling a less obvious choice. In addition to this, as students look at all three equations (specific heat capacity and thermal conductivity formulae, Newton's Law of Cooling) they are more likely to develop an understanding of the relationship between them. This students' answer to Part Two of the Problem is evidence that it is successful in achieving the learning outcomes of enabling students to think about the Physics behind equations before they apply them and developing their ability to make valid assumptions and estimations.

Part 2

In this part of the problem, we are told that since the heating system stopped working, the temperature has dropped by 4°C in the first hour, and Bob is worried about his goldfish. We are essentially asked to calculate how long Bob has before the goldfish dies.

As with the other questions in this problem, we discovered that the difficulty of the problem is dependant on how deeply you analyse it, i.e. what factors you take into account and what assumptions you make. For this question, we made several assumptions.

We assumed -

- The initial temperature inside the house was 25°C (approximately room temperature)
- The temperature outside the house was 1°C (cold winter day)
- The goldfish would ~~not~~ longer survive at temperatures less than or equal to 12°C
- That the rate of decrease in temperature of the water in the bowl is equal to that of the air in the room

In the beginning, we tried many different approaches by making different assumptions. For example, we considered taking into account the body heat of Bob and Martha, as this might affect the rate at which the temperature would drop in the room. However, we then decided that if that were the case, we would also have to take into account the affect the body heat of the fish, the difference in cooling rate of the water in the fish bowl compared to that of the air, and even the furniture, for the same reason. This, we decided, was the wrong way to go because, since we were only working with assumptions and guesses (i.e. the room's temperature, the outside temperature and the temperature at which the fish would die), the difference the body heat of a goldfish would make would be quite negligible!!

Initially, we tried using the formulae that we were most familiar with such as $Q = mc\Delta T$ and $\frac{\Delta Q}{\Delta T} = kA\frac{T_1 - T_2}{l}$, but these only gave random pieces of information ! which we couldn't relate to each other to give us any form of useful information.

In the search for an equation that would be better suited to our information, we came across Newton's Law of Cooling.

Box 3.7. Representative section of students' answer to Part Two, Problem One of the PBL thermal physics module.

3.2.4. Comments on Part Three

We designed Part Three of the Problem to enable students to gain an understanding of the effects of insulation, thermal transmittance and its relation to thermal conductivity. One of the main learning outcomes for this part of the Problem was that students would recognise thermal transmittance values (U vales) are determined experimentally and take into account the presence of an air layer on either side of the material in question. This is in contrast to thermal conductivity values, which are a measure of the thermal conductivity of the material alone and do not account for the presence of the air layer. U values can be calculated by taking the inverse of the thermal conductivity values, however when this is done, the air layer is not accounted for.

In keeping with the theme of heating a house, students are asked to decide which method of insulation will be most effective. Once again, it is "real-world" and something that some students will have previous experience of. We decided to give students a table containing the thermal transmittance values of all the relevant materials, as this data was difficult to find other than in unspecified or British Thermal units. We felt that it wouldn't be worth the effort for students looking it up. In calculating the thermal transmittance of the walls and windows of the house students will have to develop a method of summing the U values and in this way will develop an understanding of their relationship with thermal resistance values.

3.2.5. Students' answers to Part Three

Some previous experience of the topic involved in this part of the Problem, led to difficulties; for example, most groups should have looked up the meaning of thermal resistance and transmittance, but felt that they knew what they were and so didn't. However, the students soon realised that they needed a better understanding and precise definition of the concepts involved to solve the Problem and so began researching again. Most groups started by trying to calculate the energy lost from the house using the thermal conductivity formula. They looked up the thermal conductivity value for brick or glass depending on whether they were examining the heat loss through the walls or windows. They then estimated inside and outside temperatures and an area and thickness of the walls or windows and substituted into equation 3 (see section 3.2.2.) However, these groups then recognised that the values obtained using this method were much too large. They began to question their method to determine why this was so and realised that thermal transmittance rather than thermal conductivity should have been used, as it accounts for the build up of the air layer on either side of the material and so resulted in lower values. [2]

All of the groups then attempted to determine the overall thermal transmittance of the house using the U vales given. Most groups started by summing the U values of the materials in question to obtain the overall thermal transmittance of the walls and windows. However, the students soon began to question how the addition of insulation could result in a higher thermal conductivity, which was counterintuitive. As a result most groups went on to carry out more research into thermal transmittance, however some had to be asked about their results before they acted. Eventually all groups discovered the relationship between thermal transmittance and thermal resistance and the formula below:

$$U = \frac{1}{R} \tag{4}$$

The students then used this formula to determine the thermal resistance values for the materials in question, summed these and then converted back to obtain the overall thermal transmittance of the house walls and windows.

During one of the tutorial sessions, one group, after discovering that thermal transmittance rather than thermal conductivity was relevant, discovered an equation relating the two, shown below:

$$U = \frac{k}{l} \tag{5}$$

As they had used equation 3 to calculate the heat flow, they didn't see the need to use U values as they had already divided the thermal conductivity by the thickness. These students were asked to calculate the U value of one of the materials using the formula they had found (equation 5) and to look up the U value for the same material and compare the two. In doing this, the students noticed that the thermal transmittance that they had calculated was much higher than the one quoted for the material and this lead them to discover the effect of the air layers on both sides of the material.

Eventually, all groups succeeded in answering this part of the question, with seven out of the ten groups estimating the heat loss from the house using thermal transmittance. Part of a typical answer to the Problem is shown below in Box 3.8.

It is clear from the students' diagrams below in Box 3.8 that they have developed an understanding that an insulating air layer builds up on either side of the walls of the house. It is also evident from these students' answer that they know that U values account for the presence of this air layer as it is them that they use to calculate the overall thermal transmittance of the walls with and without insulation. The fact that the students add the thermal resistances of the materials rather than the thermal transmittance values is evidence that they understand that U values are not additive. However, the answer lacks any explanation from students, they don't explain why U values aren't additive or why they chose to use them. We may conclude that during Problem students had not yet adjusted to explaining their reasoning. The lack of explanation was pointed out to them during the feedback.

Walls:

The insulation value for the walls and roof is given as 8.3 for the outer surfaces and 17 for the inner surfaces. The areas of the walls and roof (minus windows and doors of course) are $90m^2$ and $50m^2$ respectively.

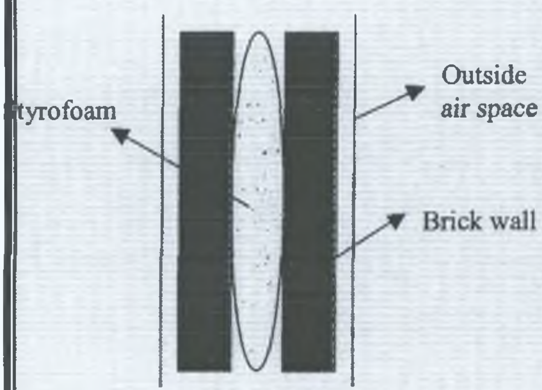
$$R = \frac{1}{U}$$ where did you get this from?

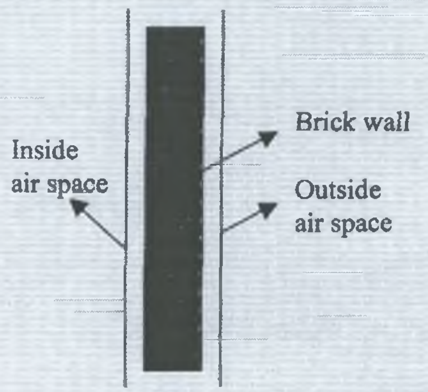
No insulation

$$R = \frac{1}{17} + \frac{1}{8.3} = 0.179, \text{ therefore } U = \frac{1}{0.179} = 5.59$$ units?

why addition?

The collective insulation value of the inner and outer walls without Styrofoam is found to be 5.59 by adding the reciprocals of the U values. With Styrofoam it is found to be 0.239. These were multiplied by the areas to find the difference in heat loss with insulated and non-insulated materials, these values were found to be 782.6 & 33.465 respectively showing that the insulated walls and roof are much more efficient. This gives a difference of 749.44





All U values are in $Wm^{-2}{}^{\circ}C^{-1}$

If the walls are insulated and the windows not there is a U value of 36.86.

If the windows are insulated and the walls not there is a U value of 796.6.

It is clear from these figures that it is more economic to insulate the wall & roof with Styrofoam.

Box 3.8. Representative section of students' answer to Part Three, Problem One of the PBL thermal Physics module.

3.2.6. Comments on Part Four

We developed the final part of the problem to enable students to think about the macroscopic effects of heat and it involves thermal expansion. Although it is the least open-ended part of the problem, it is somewhat flexible as students can decide whether the insulation resulted in all the heat loss that was previously lost being retained, or if the house has become hotter. As well as requiring the students to research into thermal expansion and carry out calculations, they are required to apply their previous knowledge to a new situation. The final question within this part of the Problem was intended to give students an understanding of thermometry. It is designed so that there is no right or wrong answer, either is correct once students explain their reasoning. In this way they develop an understanding of thermometric properties and decide for themselves if the change in length of the pendulum would be a suitable thermometer.

From observing students it was evident that they found this the least challenging part of the Problem. One of the reasons for this was that they had the previous knowledge of pendulums required to solve it and thus knew from the beginning what was required. This had a significant effect, as one of the difficulties that most groups had in answering all parts of the Problem was trying to determine where to start and what was relevant. Although students had this previous knowledge, there were other concepts involved, such as thermal expansion, which they had no formal knowledge of.

In conclusion, the Problem was challenging enough to be useful but a nice way to finish.

3.2.7. Students' answers to Part Four

No group suggested that the temperature remained constant in the house, even though it was stated in the question that the aim of the insulation was to save money on the heating bill. All ten groups assumed a slight increase in temperature and estimated the effect this would have on the length of the pendulum. The question on thermometry also worked well, in that whether students answered yes or no, they explained their reasoning clearly (see Box 3.9). Those that said 'yes' based their opinion on the principle that the expansion of the pendulum, resulting in the clock running slow, is a thermometric property and thus could be used as a measure of temperature. The groups answering 'no' realised this, but based their opinion on the fact that as the changes in length are so small they would be difficult to measure and so as a thermometer the pendulum wouldn't be very accurate or practical. Overall this part of the problem proved successful, although it wasn't as open ended as other parts of the Problem, it still required students to complete research, apply their previous knowledge and develop their own understanding of thermal expansion.

Could the pendulum be used as a thermometer?

The answer to this question is yes but it is not practical because of the subtle changes to be measured.

Here is how it could work: The time interval of a pendulums swing is directly related to its length and the length of any material is determined by the temperature it is exposed to. This means that under different temperatures the pendulums period will change, the measure of this change of period can tell us what temperature it is so long as we are supplied with the information of what the pendulum is made of so that we can determine the coefficient of expansion. Due to relatively low room temperatures the change in length of the material would be very difficult to measure accurately. What is needed here to make this practical is a material that would have a very high heat expansion rate so that more precise measurements on the pendulums change in period could be made and in return more accurate determinations on the temperature.

Box 3.9. *Representative section of students' answer to Part Four, Problem One of the PBL thermal physics module.*

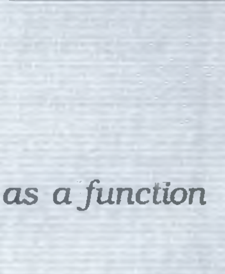
3.3. Assessment of students' understanding of thermal equilibrium

3.3.1. Introduction

Fifty per cent of the PBL module marks were awarded to a written final examination in a standard format. This exam was composed of three questions and was written with the learning outcomes of the module in mind, consequently the questions were designed to test students understanding, asking them to state and justify assumptions and apply what they had learned to new situations, rather than just perform calculations or reproduce information. Exam question one, presented below in Box 3.10, assessed students understanding of thermal equilibrium and insulation, and ability to apply Newton's Law of Cooling and draw heating and cooling curves. As solving Problem One teaches students concepts and skills their answers to the exam question may give an indication of its effectiveness.

Question One

You are investigating the insulating properties of Styrofoam in a simple experiment. You build a hollow styrofoam cube with walls made of 30 cm by 30 cm slabs of 1 cm thick styrofoam. Inside this cube you place a 25 W light bulb and a thermocouple (which you can control/read from outside the cube). You close off the hollow cube with its Styrofoam lid, switch on the light bulb and monitor the temperature as a function of time.



a) *Sketch the heat flow* into *and* out of *the Styrofoam box as a function of time in a single diagram. Explain your reasoning.*

b) *Determine the heat flow through the Styrofoam walls if the light bulb is left on for a long time. Explain your reasoning.*

After 10 minutes you switch off the light bulb. You notice that the temperature inside the cube is 57.2 °C and after a few seconds the temperature starts to decrease. Two minutes later the temperature inside the cube has dropped to 53.5 °C.

c) *Sketch the temperature the cube as a function of time from the moment you switch the light bulb off. Explain your reasoning.*

d) *Estimate the temperature inside the cube 11 minutes after switching off the light bulb. Clearly state and justify which assumptions you make.*

You repeat the experiment with another Styrofoam cube. The set-up is identical, but the Styrofoam you use is only 0.5 cm thick.

e) *Sketch the temperature inside this cube as a function of time from the moment you switch the light bulb off in the same graph you used for part c. Explain the differences and similarities between the two graphs.*

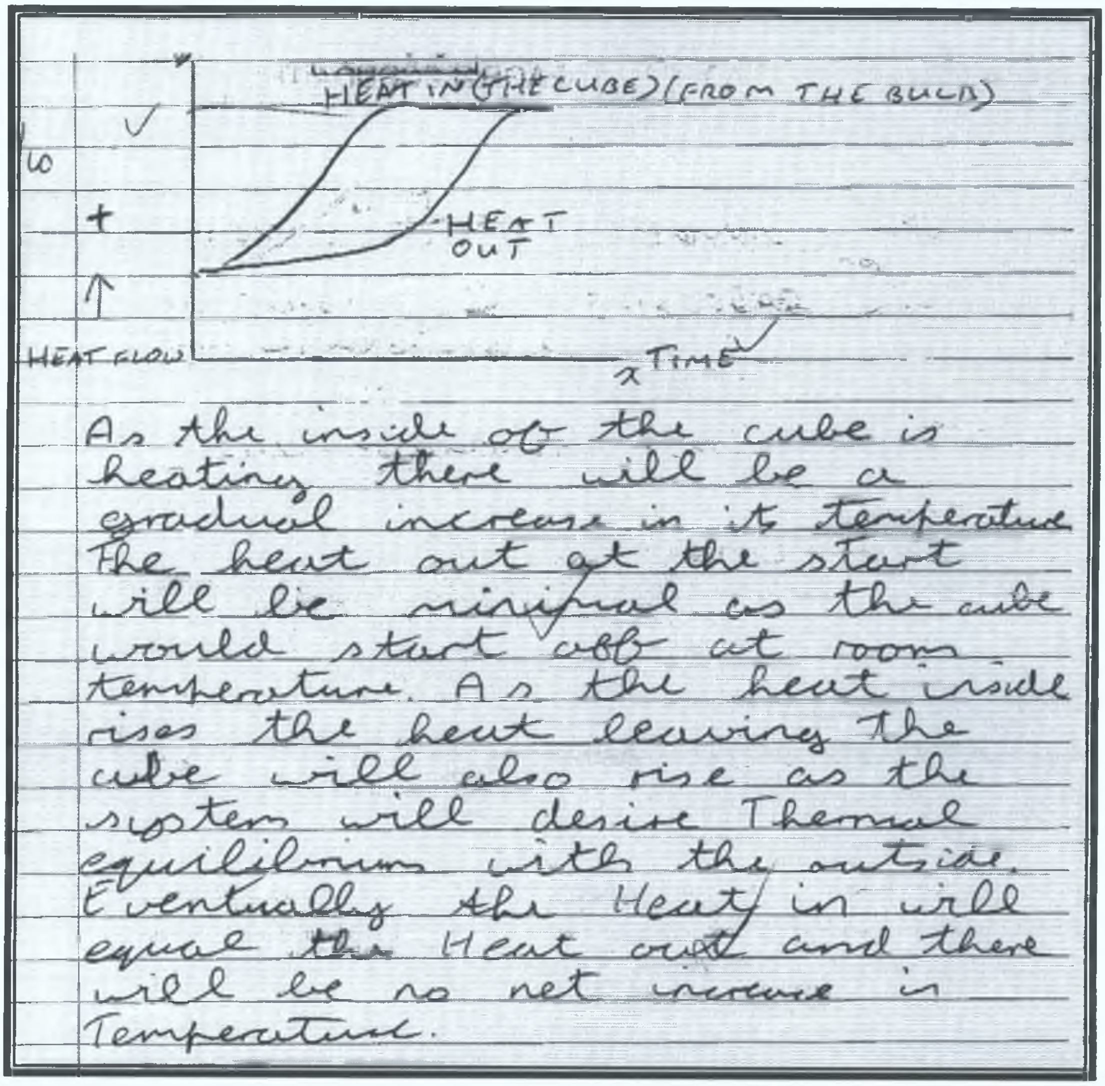
Box 3.10. *PBL thermal physics module final exam Question One.*

3.3.2. Comments on parts a and b

Part a of these questions assesses students' understanding that the box will come to thermal equilibrium with the lamp. If students realise this, they should draw the heat flow into the box as constant and show that the heat flow out levels off at the same value (see correct graph in Box 3.11 below) This is very similar to part one of Problem Four (see chapter six, section 6.2.1.) in which students are asked to determine the amount of ice required to keep a cool box at 0°C for three days. In order to solve this Problem, they have to recognise that heat will flow into the cool box from the outside until it reaches thermal equilibrium with its surroundings. To answer part a of Question One from the exam paper students must realise that heat will flow from the lamp into the Styrofoam box until they reach thermal equilibrium. The only differences between Problem Four part one and Question One from the exam paper is the source of the hot object, in Problem Four it is outside the cool box, in the exam question it is inside.

Part a of exam Question One was also similar to part two of Problem one (see section 3.2.2.) in which the students must realise that the temperature inside the house will drop until it reaches thermal equilibrium with its surroundings. The only difference between applying the concept of thermal equilibrium to this question and to Question One part a of the exam is that Problem One involves the house cooling, whereas the exam question involves the box heating.

Thus the exam question involves reasoning that students have previously employed. However, to the students exam Question One was a whole new problem, they found it difficult to relate it to the Problems which they had previously completed. The ability to apply knowledge to new situations is a skill that is not usually developed through lecture as this methodology usually involves answering typical end of the chapter questions, which are all similar to each other. However, during PBL, students are applying what they have learned to different situations. For example what the students have learned from Problem One on thermal equilibrium they have to apply to Problem Two and Problem Four. It is clear from students' answers to the exam that they were not able to transfer this knowledge in this particular situation. This seems to indicate that PBL has not improved students' ability to transfer what they have learned to new situations. This may be because the Problems that involved transfer of knowledge were too similar to each other, or students haven't had enough experience of PBL to have developed this skill. Another possible explanation is that students are used to facing final exams that have identical or very similar questions to what they have studied during term. As the question didn't correspond to a particular Problem or situation that the students had studied they assumed that it was something they hadn't studied before. There was evidence of this after the exam when students complained that the exam questions were unrelated to what they had studied during the semester.



As the inside of the cube is heating there will be a gradual increase in its temperature. The heat out at the start will be minimal as the cube would start off at room temperature. As the heat inside rises the heat leaving the cube will also rise as the system will desire Thermal equilibrium with the outside. Eventually the Heat in will equal the Heat out and there will be no net increase in Temperature.

Box 3.11. *Representative student answer to part a of Question One from the final exam of the PBL thermal physics module.*

This question also assesses students' ability to draw a heating curve, including drawing the correct shape, plotting the right quantities and correctly labelling the graph. Although none of the Problems explicitly involved graphing, most groups drew a cooling curve as part of their answer to Problem One Part Two (see section 3.2.2.). In addition to this, Problem Six involved students obtaining heating and cooling curves for two different types of aluminium (see chapter eight), although they didn't have to draw the graphs themselves they were plotted by graphing calculators. Students were required to plot heating curves for the pre and post tests of Problem Four (see chapter six, section 6.3.). Consequently, they did have some experience of plotting graphs.

In answering Problem One, all students stated that the heat flow was dependent on temperature difference and demonstrated an understanding that heat flow was coming to equilibrium exponentially. This understanding was also evident in the students' answers to the exam question, with 70% of them drawing an exponential curve for the heat into the box. Students also showed understanding of thermal equilibrium; all groups explained that if the heating remained broken the house would reach thermal equilibrium with its surroundings. However, this understanding was not evident in students response to Question One part a of the exam paper. Although 45% of students indicated that the heat into the box would be constant, only 5% stated explicitly that as time approached infinity the heat in would equal the heat out. The remaining students indicated that there was constantly no heat flow into the box. From discussions with students and the written answers of some, it became evident that they reasoned that as the inside of the box was hotter than the surroundings, no heat would flow in, which is correct for the walls of the box. However, they were neglecting the fact that there had to be heat flowing into the box from the lamp to make it hotter than the surroundings in the first place. In relation to the heat flowing out of the box, 43% of students indicated on their graphs that this levelled off, which shows some understanding that it comes to thermal equilibrium.

As students had demonstrated an understanding of thermal equilibrium and cooling in their responses and answers to Problem One, and had gained more experience of them through completing the rest of the Problems, particularly in Problem Four (see chapter six) and Six (see chapter eight) it is unlikely that they didn't have this understanding in the exam.

One of the reasons for the number of incorrect responses was students' difficulty in recognising the similarities between the exam question and the Problems that they had solved. Suggestions on methods of improving students' ability to transfer knowledge are discussed in section 9.2.4. Another reason for the difficulties may have been the fact that the question required students to represent their answer graphically. As students did not have to use their graphing skills during the module, they may have found it difficult. This was evident in some students' answers, where they drew inaccurate graphs, however explained the physics correctly.

Part b of the questions once again assesses students understanding of thermal equilibrium. To answer it all that is required is to say that the after a long period of time the box will be in thermal equilibrium with the lamp and therefore the heat into the box, will be equal to the heat leaving. As the lamp is producing 25W this will be the heat flow through the box. 32% of students stated that eventually the heat in would equal the heat out but only 9% actually gave the correct value. Of those students that didn't give the correct value, 35% calculated an incorrect value and the other 65% gave no value at all, included in this 65% are the students who spoke about thermal equilibrium.

One of the main problems that students had with this part was expecting it to be more complex than it was. A lot of students tried to calculate the heat flow due to conduction, which they found impossible, as they had none of the information necessary. There was evidence that some students were aware of the application of thermal equilibrium. 32% said that heat in would equal heat out in equilibrium and 39% said that the system would reach thermal equilibrium.

3.3.3. Comments on parts c, d and e

Part c of the problem examined students' ability to draw a correctly shaped and labelled graph. It assessed students understanding of thermal equilibrium once again as they were required to indicate the asymptote at room temperature.

Although this question assessed similar concepts to those assessed by part a, it was more familiar to the students as most of them had drawn cooling curves when solving Problem One part two. It was evident that some of the students' difficulties with part a of these questions was transferring their knowledge, as 70% of them indicated an asymptote at room temperature, indicating an understanding of thermal equilibrium, which is more than in part a. As well as this, 89% of them drew an exponential curve, compared with 70% for part a.

In general, this part of the questions didn't cause students any difficulty with the average mark being 70%. This indicates that students did gain an understanding of thermal equilibrium from Problem One, however they do find it difficult to apply it to new situations.

Part d of the exam question assessed students understanding and ability to apply Newton's Law of Cooling. As well as carrying out calculations students also had to state and justify any assumptions they were making, such as a constant outside temperature and if they were neglecting convection and radiation. 57% of students recognised the relevance of Newton's Law of Cooling and 43% correctly stated their assumptions. The most common difficulty with this part of the questions was the mathematics. Even though students demonstrated an understanding of the physics, they found it difficult to manipulate and use the formula, with only 7% of students managing to calculate the correct temperature.

The final part of the exam question assessed students understanding of a number of different concepts. It assess the same skills as part c, as students once again have to draw a graph, however it has the added aspect of testing students understanding of insulation and thermal transmittance. Students have to explain the difference and similarities between two cooling curves, obtained using differing thicknesses of insulation material. Students' answers to this question indicated that they had an understanding of thermal equilibrium with 75% indicating the same final temperature for both cubes. 75% of students also stated that the cube with the thinner walls would cool down quicker, with only 9% indicating twice as quick. This suggests that students have an understanding that the rate of cooling is not just dependent on the thickness of insulation alone. However, no students mentioned that there was a build up of an air layer on either side of the insulation which also effects the cooling rate, which is the reason why the block with walls half as thick doesn't cool down twice as quickly. The fact that students didn't state that it cooled down twice as quickly might indicate that they were aware of this, but didn't state it explicitly.

3.4. Conclusion

Students' reports on Problem One demonstrate that they have developed an understanding of thermal equilibrium, Newton's Law of Cooling and the effects of insulation. They also provide evidence of the development of students' modelling skills.

Observation of students during tutorials showed that they were beginning to carry out their own research, for example, determining what temperature goldfish cannot survive below or finding a definition of thermal transmittance. Through this they began to develop assessment skills, determining what sources of information were reliable and which were relevant. It was also evident from observation that students' group work skills were developing as they solved the Problem. As they progressed through the problem solving process they began to make the most of their time, assigning tasks to different members, and discussing possible ways of approaching the Problem together.

It can be concluded that Problem One was successful in making students think about the physics concepts involved, it also introduced them to modelling. It was clear from the reports on Problem One that students had not yet developed the skill of explaining their reasoning, however by the exam most students had. This shows that PBL was effective in improving this. However, there was evidence in the exam that students found applying what they had learned in this Problem to a new situation difficult.

References:

1. P. van Kampen, C. Banahan, M. Kelly, E. McLoughlin and E. O' Leary *"Teaching a single physics module through Problem Based Learning in a lecture-based curriculum"* American Journal of Physics 2004 Volume 72, Issue 6, pg. 829-834
2. Insulation information (Online) http://www.sustainableconstruction.co.uk/Units%20and%20Measures.htm

Chapter Four Discussion of Problem Two

4.1. Introduction to Problem Two

Problem Two is presented in Box 4.1 below. Its chief aim is to introduce students to the Ideal Gas Law, and the concept of heat balance. The problem draws heavily on previously acquired knowledge of heat transfer (from Problem One) and Archimedes' principle (from a previous module or secondary school physics). As with all of our Problems, its aim is to further develop the students' research skills and to make them think about the effects of simplifications and assumptions on numerical calculations.

Student difficulties with Archimedes' principle are well-documented and have been quantified in a pre/post test method by Loverude *et al*[1]. They found in particular that students tend to confuse buoyancy and buoyant force; (mass) density and volume; and that they fail to recognise that it is the volume of *displaced* fluid that is relevant. Problem Two does not directly address these issues, which gives us an interesting opportunity to investigate whether the knowledge gained from an in-depth study of a problem that uses Archimedes' principle transfers to a deeper understanding applicable to a different situation. We will discuss the results from our study in section 4.4 but will look in detail at the student difficulties with the thermal physics and the Problem itself first.

Thermal Physics – Problem Two

Part One

You are doing some research in the library and you come across an article on Steve Fossett's solo circumnavigation of the world in a hot air balloon. You think that this was an amazing achievement and become really interested in hot air ballooning.

After some investigation into the topic you decide to build your own hot air balloon. You start off with modelling a simple airship: essentially a basket which is underneath a balloon called "the envelope" made of 1 mm thick Mylar. Why is Mylar a good choice of material? What factors determine the volume of the balloon that you need to float at a given height?

Part Two

You decide that you would like to float at a height of about 2 km. You use a propane burner to heat the air inside the balloon, but for safety reasons you don't want to exceed a temperature of 150°C. Estimate the minimum number of square meters of material you need to do this if the bottom of the balloon is open

Part Three

Determine the heat loss per hour from the balloon in flight.

Box 4.1. *Problem Two of the PBL thermal physics module*

4.2. Students' response to Problem Two

4.2.1. Comments on Part One

Immediately after students were pre-tested (see section 4.3) they were given Problem Two in its entirety. This caused no problems, as Parts Two and Three don't provide any indication as to the possible answers to Part One.

Part One of the problem serves as an introduction as well as a basis for the second part of the problem; it requires students to think about what makes bodies float and why volume is a relevant factor. We gave them the model of the basket and envelope to ensure that they avoided choosing a complex model for their balloons. It encourages students to think about the physics of the situation without involving equations or calculations. To stimulate this even further, we added in a sub-question on the desirable properties of Mylar; otherwise the question was unchanged from the previous year.

From observing the students during their PBL tutorials, we saw that they found this part of the problem quite challenging. Although it was designed to serve as a simple introduction, some groups, particularly the Science Education students, had problems with it. The main difficulty that students had was trying to determine why volume was relevant. Although all students had previously studied Archimedes principle, it became clear that they didn't have a functional understanding of it. However once students started discussing their ideas with facilitators, they began to form an understanding of the concepts needed to solve the problem.

4.2.2. Students' answers to Part One

All ten groups answered this part of the problem well and none of them included formulae. A representative student answer to part one of the Problem is shown below in Box 4.2. These students researched into Mylar in detail. It was evident from their report and those of other students that this introductory question was effective in requiring students to carry out research. Regarding listing the factors affecting the volume of the balloon required to lift off: all groups listed some of those relevant to the air, both inside and outside the balloon, such as temperature, pressure and density, however most groups didn't explain them fully. As in the students answer below in Box 4.2, students listed things such as air temperature, without stating if it was inside or outside the balloon or why it was relevant to the volume required to lift off. One of the reasons that students didn't explain the relevance of the factors may have been because the question only asks them to list them and so they may have considered further explanation unnecessary. Another reason for the lack of explanations given by students may have been that they intuitively considered factors such as air density as relevant to the floating of the balloon without really understanding why. We feel that this may have been the case in some circumstances, as students' responses to the pre tests (see section 4.4) indicated that they didn't have a full understanding of Archimedes Principle. However, the next part of the problem (see section 4.2.3) requires an understanding of how these factors, (air temperature, pressure and density inside and outside the balloon) relate to the required volume to lift off and so this ensured that students thought about their relevance.

In relation to the thermal physics, students realised that volume was an important factor and that they could determine it using the Ideal Gas Law, since the pressure and temperature of the air in the balloon affect the volume of the gas. All of the groups mentioned that either the density or the temperature and pressure of the air inside or outside the balloon, would be factors that affected the volume required to reach a given height.

1.1 Physical properties of Mylar®.

Mylar® is a polyester film. It is very tough and retains this toughness even over high temperatures. The temperatures at which it can retain its physical properties range from –70 degrees all the way up to 150 degrees. It is also lightweight, very durable but tear and puncture resistant. Mylar® is impermeable to air and moisture resistant making it an excellent material for use in hot air ballooning. Some of the properties of Mylar® are listed in the table below;

Property	Value	Unit
Density	1.390	g/cm^3
Melt point	254	°C
Specific heat	0.28	Cal/g/ °C
Thermal conductivity	0.00037	Cal cm/cm^{2}sec °C

use SI units!

1.2 Factors effecting volume of balloon required

The factors of the volume of balloon required are

1. The mass of the objects being lifted. This includes the basket, the equipment and the passengers being lifted✓
2. The air temperature ✓
3. The volume of the air → ?
4. The air pressure ✓

Box 4.2. Representative student answer to Part One of Problem Two of the thermal Physics module.

4.2.3. Comments on Part Two

We decided to reformulate this part of the Problem. As for part two of Problem One (see section 3.2.3.), we decided to take out information to make the problem more open-ended. This meant that students had to decide for themselves on reasonable inside and outside temperatures, they also had to consider the effects of altitude on pressure and temperature and whether they would require a larger or smaller volume of air to float at higher altitudes.

The students' lack of understanding of Archimedes Principle was evident as they tried to solve this problem. Below, in Box 4.3 is an extract taken from observation notes written after one of the tutorials.

> *Two groups were looking at the Archimedes Principle and trying to relate it to the hot air balloon with some difficulty. They knew that the buoyant force was equal to the weight of the displaced fluid but couldn't see that this was the weight of displaced air and that this was equal to the density of the air times the volume of the balloon times acceleration due to gravity. When asked how they were able to work out the buoyant force on a stone submersed in water however, they were able to do it. It seemed that they could apply Archimedes Principle to familiar situations because they had done it before, or seen the answer but could not apply it to a new situation as they didn't really have an understanding of it. This was the case with most of the groups.*

Box 4.3. *Notes on students' attempts at applying Archimedes Principle to solving Part Two of Problem Two of the PBL thermal physics module.*

As can be seen from the above extract students are neither able to recognise that the relevant volume is that of the displaced fluid, nor to recognise the relationship between mass, density and volume in order to calculate this. It was clear that while they were able to state Archimedes Principle with ease, they didn't have a functional understanding of it. We found that the problems the students were having with floatation were similar to those documented by Loverude *et al*[1]; these are discussed in section 4.4. However, with the guidance of the facilitators, students were able to solve the problem and all groups managed to calculate the required surface area of material.

There were no serious student difficulties concerning the thermal physics aspects of this part of the problem. Most groups automatically chose the Ideal Gas Law to determine the density of the air inside and outside the balloon. They were encouraged by facilitators to justify their use of the Ideal Gas Law; their reports showed that they did.

The one difficulty that students had was manipulating the Ideal Gas Law to obtain an expression for density in terms of pressure and temperature. The main problem was that students did not realise that they could work out the density from the molar mass of air (see Box 4.4 below) and were trying to approach the problem by calculating the number of moles of air inside the balloon, which wasn't possible, as they didn't know the mass.

(1)	$pV = nRT$	Where: p = pressure, V = volume, n = no. of moles, R = gas constant and T = temperature
(2)	$\frac{n}{V} = \frac{p}{RT}$	Obtained from re-writing equation 1
(3)	$m = n.M$	Where: m = mass and M = molar mass
(4)	$\rho = \frac{m}{V} = \frac{nM}{V} = \frac{pM}{RT}$	

Box 4.4. *Manipulation of the Ideal Gas Law to obtain an expression for the density of a gas in terms of pressure and temperature.*

4.2.4. Students' answers to Part Two

All groups overcame their difficulties with Archimedes Principle and manipulating the Ideal Gas Law and calculated the surface area of a balloon required to float at a given height. A representative student answer is shown below in Box 4.5. These students give an introduction, state that they have discussed the Problem amongst themselves and explain exactly what they are doing and why. In line four the phrase "we discussed that the fact that for the balloon to take off the ground, the buoyancy force (upward pushing force) must be greater than the weight of the balloon and the weight of the basket (plus the burner, fuel and anything else you wish to bring up with you)" shows that the Problems are encouraging students to work together. The students also appear to think about the situation rather than using formulae automatically. In addition to the introduction to the formula students also explain how Archimedes Principle relates to the balloon in line eleven. These students went on to complete this part of the Problem by deriving an expression for the volume of the balloon in terms of the mass of the basket and the density of the hot and cold air.

As we are asked to calculate the amount of material required to fly the balloon 2 km high we came to the conclusion that this will require us to calculate the volume of air in the balloon when it is 2 km high.

To do this we discussed the fact that for the balloon to take off the ground, the buoyancy force (upward pushing force) must be greater than the weight of the balloon and the weight of the basket (plus the burner, fuel and anything else you wish to bring up with you)

Putting this into a formula:

$$F_B > W_{basket} + W_{balloon} \qquad \text{Eqn 1}$$

After much researching we came across Archimedes' principle (giancoli pg 283). This principle states that the buoyant force of a body immersed in a fluid is equal to the weight of the fluid displaced by that object. This means that the buoyant force that causes the balloon to rise is equal to weight of the air that the balloon displaces

i.e. $F_B = mass_{air\ (outside\ balloon)} * g$ (g = gravity)

acceleration due gravity

And as mass is equal to density * volume

Then: $F_B = density_{(cold\ air)} * volume_{balloon} * g$

The weight of the basket can be written as $mass_{basket} * g$

And the weight of the balloon can be written as $mass_{balloon} * g$

Again as mass = density * volume

We can write the weight of the balloon as $density_{hot\ air(in\ balloon)} * volume_{balloon}$

This means we can now write Eqn 1 as follows:

$$Density_{cold\ air} * volume_{balloon} * g > mass_{basket} * g + density_{hot\ air} * volume_{\ balloon} * g$$

We can use the symbol ρ for density and V for volume ?

Box 4.5. *Section of students' answer to Part Two of Problem Two.*

In order to calculate the density of the air surrounding the balloon students had to find out the temperature and pressure at the given height. We hoped that some of the groups would use the Boltzmann factor in order to do this (see Box 4.6); three of the ten did. Most of the other groups just looked up the pressure at two kilometres. We didn't insist on students using the Boltzmann factor as it wasn't one of the learning outcomes of the Problem. We decided that if students used it, it would be an extra benefit, however if they just looked up the pressure, this would be acceptable.

Boltzmann Equation: $p = p_0 e^{\left(-\frac{mgh}{kT}\right)}$

Where:

p = unknown pressure

p_0 = pressure at ground level

T = temperature at given height

m = average mass of the molecules present in the gas

g = acceleration due to gravity

h = height from ground

k = Boltzmann's constant

OR: $p = p_0 e^{\left(-\frac{Mgh}{RT}\right)}$

Where:

M = molar mass

R = gas constant

Box 4.6. *The Boltzmann Equation, which can be used to calculate pressure at a given altitude.*

All the groups' responses were similar to the one shown in Box 4.5 and it was evident from students' reports that the Problem was effective in enabling them to gain an understanding of Archimedes principle in relation to this specific Problem as well as knowledge of the Ideal Gas Law and its applicability.

4.2.5. Comments on Part Three

We designed the final part of the Problem to enable students to build upon their knowledge of heat transfer that they had gained from Problem One. We changed the original question to ask students to determine the heat loss per hour from the balloon, rather than calculating the amount of fuel required to travel for one hour, to encourage students to think about the fact that at equilibrium the heat input into the balloon would equal the heat lost. The question was also designed so that it would develop students modelling skills and so that they would realise the effects of assumptions and simplifications on their calculations.

4.2.6. Students' answers to Part Three

The changes made to this part of the Problem worked well, although the students did find it challenging. The difficulty with the new version was that students found it difficult to begin, as they needed to realise that the heat into the balloon is equal to the heat lost. Changes could be made to this part of the problem to ensure that students don't find it as challenging. Students could be given some information, such as the average amount of fuel to keep a balloon in the air for an hour, or maybe guided a little more, firstly asked why fuel is necessary to keep the balloon in flight. However, these changes could lead to the problem becoming prescriptive and it is important that it remains open-ended. One aspect that could be changed is the time given to this part of the Problem.

Most groups started this problem by thinking about calculating the heat loss from the balloon but these students soon ran into difficulty, as modelling the heat loss from a balloon is complex. Students then thought of concentrating on conduction as the main method of heat transfer and ignoring convection and radiation however this resulted in an inaccurate answer as convection plays an important role. This is evidenced by the answers of groups who modelled the heat loss by heat input obtained (see Box 4.9 below), which were much larger than those obtained by students who only took conduction into account (see Box 4.8

below). Although most groups realised that this was the case, they found it difficult to develop another method of answering the question. The three Science Education groups managed to determine the heat loss from the balloon by realising that in equilibrium the heat in is equal to the heat out. This was because one of the groups had discussed their ideas on the topic with a facilitator. The facilitator guided the students towards thinking about a heat balance approach by asking them to think about how the question related to the heat loss from the house in Problem One. As a result the students began to think about the fact that heat was lost from the house until it reached thermal equilibrium with the surroundings. This led them to think about the balloon losing heat to its surroundings. The group also had to be asked what was being done to the balloon to keep it at a constant temperature. In answering this question the students realised that the heat entering the balloon is equal to that leaving. The group that were guided by the facilitator then peer tutored their classmates and this is why the three Science Education groups answered the question in the same manner.

$$\frac{\Delta Q}{\Delta t} = kA\frac{T_1 - T_2}{l} \longrightarrow \text{is that applicable ??}$$

$$= (3.7\text{x}10^{-8})(667)\frac{(150-1)}{1\text{x}10^{-3}}$$

$$= 3.68\ \text{Js}^{-1}$$

very low.

Box 4.8. *Typical student response to Part Three of Problem Two of the PBL thermal physics module.*

It is evident from the students answer below in Box 4.9 that they are applying knowledge that they have gained from Problem One. The introduction that they give shows that they have thought about conduction and convection and how they apply to heat loss from the balloon. (The fact that they were looking for a U value, evidence by line fifteen, shows that they have developed an understanding that thermal transmittance rather than thermal conductivity is more appropriate in determining heat flow through conduction.)

Heat loss per hour of the balloon in flight.

A hot air balloon is a complex system as regards heat loss.
Heat loss occurs in two main ways – conduction and convection
Heat loss by conduction is proportional to the temperature difference between the balloon and the surrounding air, through the surface area exposure of the envelope. The proportionality constant would have to be experimentally determined.
And by convection of hot air escaping out of the bottom of the balloon bag.
Also the hot air near the surface of the balloon heats the layer of air adjacent to it causing its density to decrease so it rises and is replaced with cold air which is in turn heated and so on.
Effects of the porosity of Mylar (negligible)
The weather also affects the severity of heat loss. If there are strong winds the warm air layer at the surface of the envelope would be continually replaced by cold air, so we are assuming that it is a lovely calm fine day.

To calculate the heat loss we first tried to find the U-value for Mylar, which we were unable to find. The system is too complex for this approach. So we decided to look at it from a different angle.
The only reason the balloon loses altitude is by loss of heat. To maintain a certain height heat is added to compensate for this loss. So by determining the amount of fuel added to keep the balloon at 2km we will have found the heat loss.

Heat added = Heat lost ✓

If we know the volume of fuel used in one hour, we can multiply this by the Specific Heat of Combustion of Propane, to give the heat generated by the burning of the fuel.
The heat generated by the fuel in one hour is equal to the heat lost by the balloon in one hour.

By researching the web we found that the average volume of propane needed to keep a balloon in flight for one hour is 15 gallons(US) (REF: www.launch.net)
Since 1 gallon(US) = 3.79litres
Therefore 15gallons(US) = 15 gallons x 3.79 l/gallon = 56.85l

The chemical formula of Propane is C_3H_8
The molecular weight of propane is 44.049g/mole
The heat of combustion of propane is 2200KJmol^{-1} (REF: www.onlink.net)

Heat of combustion requires us to use *moles*, so we must convert 56.65l to moles.

The liquid density of Propane is 0.505 kg/l (REF: www.supergas.com)

Therefore the mass of our propane = Density x Volume
= 0.505 kg/l x 56.85l = 28.71kg (14)

The number of moles of Propane is equal to $\frac{weight\ of\ propane\ used}{molecular\ weight\ of\ propane}$ (15)

$$= \frac{28710}{44.094 gmole^{-1}} = 651.79 moles$$

Heat produced by burning 56.85l propane = 651.79 moles x $2200 KJmol^{-1}$
= 1.43×10^{6} KJ

Heat added = 1.43×10^{6} KJ
So, Heat loss = 1.43×10^{6} KJ

Box 4.9. *Alternative student response to part three of Problem Two of the PBL thermal physics module.*

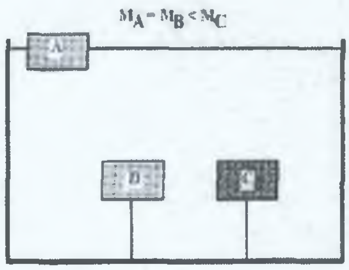
4.3. Assessment of students' understanding of Archimedes Principle

4.3.1. Pre and post tests for Problem Two

Problem Two was the first problem that we pre and post tested. At this stage students didn't have any prior formal instruction in thermal physics and so had little formal pre-knowledge that could be tested. Instead we used pre and post tests on Archimedes Principle. We used those developed by Loverude *et al*[1] so we could compare our results with those reported.

Loverude *et al* document the development of students' understanding of Archimedes Principle as well as the misunderstandings students commonly have after formal instruction in this topic. In their study students were given a number of tests, post instruction, in order to identify their difficulties and how well they understood the concept. We decided that we would use two of these tests as our pre and post-tests for Problem Two; these are shown below Box 4.10 As the pre and post tests probe the understanding of the same principles we gave half the students test A as a pre test and half test B and vice versa for the post test.

Test A

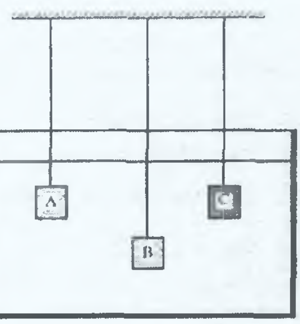


Two blocks are attached to strings as shown above. A third block floats at the top of the water. The blocks all have the same size and shape and have all been previously observed to float in water. Blocks A and B have the same mass and block C has a greater mass. Blocks B and C are at the same level.

Is the buoyant force exerted on block A greater than, less than or equal to the buoyant force exerted on block B? Is the buoyant force on block B greater than, less than or equal to the buoyant force exerted on block C? Explain.

Test B

Three cubical blocks of equal volume are suspended from strings. Blocks A and B have the same mass and block C has less mass. Each block is lowered into a fish tank to the depth shown in the figure below.



Rank the buoyant forces acting on each block from largest to smallest. If any two buoyant forces are equal indicate that explicitly. Explain.

Box 4.10. *Pre and Post Tests probing the understanding of Archimedes Principle*[1].

4.3.2. Correct answer and concepts assessed by Test A

Test A involves ranking the buoyant forces on blocks of different mass submerged at the same level and also of two blocks of the same mass, one submerged and one floating. A representative correct answer is presented below in Box 4.11.

The buoyant force experienced by a body in a fluid is equal to the weight of the fluid displaced by the body,

$$F_{buoy} = \rho_{fluid} V_{displaced} g$$

As water is an (almost) incompressible fluid, its density is constant and blocks B and C have the same volume, therefore they experience the same buoyant force

$$F_{buoy,B} = F_{buoy,C}$$

Block A displaces a smaller volume of water than B or C, as it is only partially submerged and so experiences a smaller buoyant force; therefore

$$F_{buoy,A} \langle F_{buoy,B} = F_{buoy,C}$$

Box 4.11. *Correct Answer to Test A Problem Two.*

This test assesses students understanding that it is the weight of the *displaced* fluid that the buoyant force is dependent on. As the density of the liquid is constant the weight of the fluid is dependent on the volume and so the buoyant force is equal to the volume of the displaced fluid. Students must recognise that even though two blocks have the same mass, as one is displacing less fluid it is experiencing the lesser buoyant force. The fact that students also have to realise that the buoyant forces acting on block B and C are the same even though block C has more mass, also tests if they are aware that it is the mass of the fluid displaced rather than the mass of the object itself. Finally students must also understand the relationship between mass, density and volume.

4.3.3. Correct answer and concepts assessed in Test B

A representative correct answer to test B is presented below in Box 4.12. Once again this tests assess students understanding that it is the volume of the *displaced* fluid that is relevant. Although blocks A and B have more mass than C, they displaced the same volume of water and so experience equal buoyant forces. While block B is at a greater depth than the other two, it still experiences the same buoyant force: water is an incompressible fluid and therefore the weight of the water displaced by block B is identical to the weight of the water displaced by blocks A and C. If the density of the water was not constant then the depth would have an effect, at a lower density the same amount of displaced fluid would result in a smaller buoyant force.

The buoyant force experienced by a body in a fluid is equal to the weight of the fluid displaced by the body,

$$F_{bouy} = \rho_{fluid\ displaced} V_{fluid\ displaced}\, g$$

As water is an (almost) incompressible fluid, its density is constant and blocks A, B and C have the same volume; therefore they experience the same buoyant force

$$F_{buoy,A} = F_{buoy,B} = F_{buoy,C}$$

Box 4.12. *Correct answer to test B Problem Two.*

4.3.4. Concepts relating to Archimedes Principle contained in Problem Two

Although the problem was not designed to specifically address student difficulties with Archimedes Principle, it did deal with certain aspects in common with the pre and post tests. The concepts, which are addressed by the Problem and the pre and post tests are marked out in Table 4.1 below.

Concepts	**Test A**	**Test B**	**Problem**
Relevant volume is that of the *displaced* fluid	√	√	√
Distinguishing between buoyant force and buoyancy	√	√	√
Partially submerged bodies	√		
Relationship between mass, density and volume	√	√	√

Table 4.1 Concepts addressed in the pre and post tests and Problem Two.

4.4. Comparison of the findings of Loverude et al with our results

Loverude *et al* found that after all instruction, 20% of their first year students (algebra based physics, up to 200 per lecture) and 60% of their second year students (calculus based physics, up to 60 per lecture) could correctly rank the buoyant forces on the blocks in the questions we used as pre and post tests. They also found that the mistakes made by students were similar in nature and could be related to three main themes of the questions; blocks of different mass submerged at the same depth, blocks of the same mass submerged at different depths and identical blocks fully and partially submerged.

4.4.1. Blocks of different mass submerged at the same depth (Test A and B)

When our findings are compared to those of Loverude *et al* (see Table 4.2.) we have less correct responses overall, post instruction. One of the reasons for this may be that the problem does not directly address some of the issues with Archimedes Principle, (see Table 4.1.) whereas the tutorial given by Loverude *et al* was designed specifically to do so. The number of our second year Science Education students who could correctly rank the buoyant forces acting on each block increased after they completed the problem, however the number of our first year Physics students decreased.

	Loverude et al (Post)		Our Findings (Pre)		Our Findings (Post)	
	1st Years	2nd Years	1st Years	2nd Years	1st Years	2nd Years
Percentage of correct responses	35%	65%	22%	0%	9%	14%
Confusing mass, density and volume	-	-	39%	38%	9%	21%
More massive block results in greater buoyant force	45%	20%	35%	25%	57%	86%
Failure to distinguish buoyant force from buoyancy	-	-	26%	50%	17%	14%

Table 4.2. *Results of pre and post tests A and B on students' understanding of buoyant forces on bodies of the different mass at the same depth.*

The most common incorrect answer was that the more massive block would experience the greater buoyant force. This may indicate that completing the problem caused some confusion regarding the relationship between buoyant force and mass. This misconception has been reported by Loverude *et al*, but it is clearly not something we want this Problem to promote. It is not difficult to see why the Problem may just do that: water, which is the fluid in the pre and post tests, is an incompressible fluid, but the fluid in the Problem is air, which is compressible. The Problem required our students to calculate the volume of air required to float at a given height. As air is compressible, its density is lower with higher altitude. The students thus found that a lower mass and hence lower density of hot air was required to balance the smaller buoyant force at altitude. It appears that many students transferred the "knowledge" that fluid density increases with depth to the incompressible fluid, without questioning the physical principles. Other common errors documented in the paper by Loverude *et al* were:

- Failure to distinguish buoyant force from buoyancy
- Misuse of formulae
- Failure to distinguish between mass, density and volume

These mistakes were also evident in our students' responses to the pre and post tests; however there was an improvement after students completed the problem. (see Table 4.2 above)

4.4.2. Blocks of the same mass submerged at different depths (Test B)

Loverude *et al* found that 55% of their first year students and 80% of their second year students correctly answered that the buoyant force on blocks of the same mass at different depths would be equal in their pre test. Before completing Problem Two, none of our students correctly answered the question, and after instruction only one student was successful. Once again the most common incorrect answer was that the greater depth would result in the greater buoyant force. Probable reasons were outlined in section 4.4.1.

	Loverude et al (Post)		***Our Findings (Pre)***	***Our Findings (Post)***
	1st Years	**2nd Years**	**1st and 2nd Years**	**1st and 2nd Years**
Percentage of correct responses	55%	80%	0%	5%
Greater buoyant force due to greater depth	30%	15%	86%	42%
Greater buoyant force due to lesser depth	-	-	29%	5%

Table 4.3. *Results of Pre and Post test B on students' understanding of buoyant forces on bodies of the same mass at different depths.*

4.4.3. Identical blocks fully and partially submerged (Test A)

Only 19% of our first years and none of our second years correctly answered this question as a pre test, this is compared to 60% of the first years and 80% of the second years reported on by Loverude *et al*. One of the possible reasons for this could be that Loverude administered the tests shortly after the lecture-based instruction was completed whereas our students hadn't studied Archimedes Principle for at least a year before they were given the pre tests.

Test A was also used as a post test. Completing the Problem had no effect on the number of students answering it correctly; this is not surprising, as although they had now studied Archimedes Principle, the Problem did not deal with it in this specific context (see Table 4.1). Despite this, the number of students giving correct answers albeit with incorrect explanations rose after completing the Problem (see Table 4.4) which suggests that they may have gained some understanding without giving evidence for it in their written answers.

	Loverude et al (Post)		*Our Findings (Pre)*	*Our Findings (Post)*
	1st Years	**2nd Years**	**1st and 2nd Years**	**1st and 2nd Years**
Number of correct answers and explanation	60%	80%	16%	17%
Number of correct answers only	-	-	21%	67%
Failure to recognise that volume is the relevant factor	-	-	42%	44%
Tension in a string holding an object affects it buoyant force	-	-	32%	22%

Table 4.4. *Results of test A on students' understanding of buoyant forces on identical bodies fully and partially submerged.*

4.4.4. Comparison of Science Education and Physics students' responses

One difference between the Science Education students and the Physics students that became apparent from the pre and post-tests is their use of formulae. No Science Education students attempted to use formulae in answering the Test A pre test, compared to 25% of Physics students. However, after completing the problem the number of Physics students using formulae dropped to 22% and Science Education students rose to 78%. This was reversed in relation to Test B, with the number of Science Education students using formulae remaining constant pre and post at 60% and the number of Physics students using formulae increasing from 14% before the problem to 57% after the Problem. On both occasions the misuse of formulae dropped after students had completed the problem. Apart from this difference in resorting to applying formulae, there were no other major differences between the Science Education and the Physics students' responses.

4.4.5. Conclusions from the pre and post tests results

It can be seen from the pre and post test results that completing the Problem has not improved students' ability to apply Archimedes Principle. We feel that there are reasonable explanations for this however. Firstly, the Problem's main purpose was to introduce students to the Ideal Gas Law; although it does involve Archimedes Principle it does not seek to address all student difficulties directly (see Table 4.1). In addition to this, it was a long period of time after the original instruction had been given when the tests were administered.

However, it can be seen from the post-tests that some of students misunderstandings were helped, such as differentiating between mass, density and volume and confusion between the relationship between buoyant force and depth. This was encouraging as the misunderstandings that were alleviated were regarding concepts that the Problem dealt with. Any misunderstandings that the students had after completing the problem were relating to aspects of Archimedes Principle that weren't covered in the Problem such as the effect of incompressibility of fluids on buoyant force and buoyant forces of partially submerged bodies.

4.4.6. Recommendations for the pre and post tests

The pre and post tests were appropriate for determining the effect of Problem Two on students understanding of Archimedes Principle. However, they did involve some transfer of knowledge by the students as the Problem was set in a different context. This gave us the opportunity to determine if the students could use the knowledge that they had gained from through solving the Problem in a situation that was new to them. From the results of the post test it seems that they can to an extent. Although students didn't have to deal with objects of different mass in the Problem there was still an improvement in their responses to the tests after they had completed the problem. However, in situations were the context differed significantly such as when the compressibility of the fluid became relevant in Test B, or with the partially submerged body in Test A, then students did display difficulty with transferring their knowledge. In order to make the analysis of the results simpler the tests could be reformulated to relate to a compressible rather than incompressible fluid and so no transfer of knowledge would be required. However, if the tests were adapted they couldn't be compared with Loverude *et al's* findings, which would be a disadvantage. Another aspect to having the pre and post test suited exactly to the Problem is that an increase in correct responses to the post tests may be a result of the students having experienced a very similar question in answering the Problem and may demonstrate and ability to reproduce answers rather than display that learning has occurred.

Developing a different set of tests based on another aspect of the Problem that plays a more in-depth role may be valuable in assessing the appropriateness of the Problem to those learning outcomes not related to Archimedes Principle, such as students understanding of the Ideal Gas Law. However, this could be difficult considering students little prior knowledge of the topics covered in the Problem.

4.5. Conclusion

Pre and post test results indicate that Problem Two did not improve students' ability to apply Archimedes Principle. However, the main objective was achieved as students developed an understanding of the Ideal Gas Law, as evidenced from the results of the pre test of Problem Three, which also served as a post test to Problem Two (see section 5.3.5)

Reference:

1. M. Loverude, C. Kautz and P. Heron "Helping students develop an understanding of Archimedes' principle. I. Research on student understanding" American Journal of Physics 2003, Volume 71, Issue 11, pg. 1178-1187

Chapter Five Discussion of Problem Three

5. 1. Introduction to Problem Three

Problem Three, shown below in Box 5.1, deals with the First Law of Thermodynamics and how it can be applied to calculate the work done on a gas. The difference between state and process variables is another important aspect to the Problem as well as how different variables such as temperature, volume and pressure may be altered to bring the gas to a certain state. Adiabatic and isothermal processes are included. In addition to this, students are also required to use the Ideal Gas Law throughout the Problem and so it serves as a revision of, and addition to, the students' knowledge gained from Problem Two.

We decided that an appropriate way to introduce students to thermodynamic processes would be through a problem based on experimental work. The Problem is based around classroom demonstrations that the students are to devise. This Problem was successful during the first delivery of the module and consequently we didn't make any changes. However, we wrote a version of the Problem in the context of students as tutors to make it relevant to the Applied Physics and Physics with Astronomy students (see Box 5.1)

Thermal Physics – Problem Three

You are giving grinds to some students studying thermal physics. They are having problems with some of the concepts so you decide to prepare a demonstration to show them some of the effects of heating a gas. The following equipment is available to you: a calorimeter, a Pyrex test tube equipped with a lightweight plastic piston, a thermocouple, a stopper, a Bunsen burner, clamps and retort stands

Part One

The first stage of your experiment is designed to show the effects of adding heat to a gas at constant pressure. Sketch a simple experimental set-up that will allow you to demonstrate this to your students. Make sure that effects will be clearly noticeable

Part Two

The second stage of your experiment is designed to show the effects of adding heat to a gas at constant volume. Sketch a simple experimental set-up that will allow you to demonstrate this. Indicate how your students can work out the temperature and pressure in the test tube after your experiment.

Part Three

In the third stage of your experiment you wish to demonstrate isothermal processes as well as the difference between process variables and state variables. Describe a simple experiment that will allow you to demonstrate this, e.g. using the test tube you've prepared in part two.

Part Four

A common error made by your students is the assumption that if the temperature of a system changes, some heat transfer must have occurred. Design an experiment to rectify this misconception

Part Five

After the demonstration, you decide to ask your students a thermodynamics question to do before you give them their next lesson. You give them initial and final states for the system, along with the change in internal energy. Can they work out whether the energy change was due to the applied heat or the work done on the system? Discuss this in relation to the first law of thermodynamics.

Box 5.1. *Problem Three of the PBL thermal physics module.*

5.2 Students' response to Problem Three

5.2.1. Comments on Part One

Students were pre-tested (see section 5.3) and then given Problem Three in its entirety, as no part of the question gave any indication as to the answers to the others. We designed part one of the Problem to introduce students to constant pressure processes. It requires students to determine the effects of adding heat to a gas at constant pressure in order that they can develop a method of demonstrating them. The fact that students had to demonstrate the effects meant that they had to have an in-depth understanding of the process. Another aspect to this question is that students have to determine a method of ensuring constant pressure throughout the process, which leads them to think about how and why the pressure remains constant and introduces them to quasi-static equilibrium processes.

Students tended to think about the Ideal Gas Law right away, as they had seen it in the last Problem and we encouraged them to think about if and why it was applicable. Once students did this, they found determining the effects of heating the gas relatively simple, although they found it challenging to devise a demonstration that would clearly show them. The most common difficulty students had was understanding how and why pressure remained constant, although volume was increasing. Student difficulties with reasoning about thermodynamic processes are well established and the problems that our students were having were similar to those reported by Rozier and Viennot[1]. During tutorials, as well as during pre tests (see section 5.3) many students showed signs of incorrect linear reasoning. For example, in relation to part one of the Problem, students reasoned that the temperature increase resulted in a pressure increase, which led to a volume increase, although they were told that the process was at constant pressure.

5.2.2. Students' answers to Part One

All students succeeded in manipulating the Ideal Gas Law and determined the effects of heating the gas on volume and temperature as well as developing a valid method of demonstrating this. However, two of the learning outcomes for this part of the Problem were missing from students' reports. Students did not show explicitly that they understood why the Ideal Gas Law was applicable or that the pressure was constant throughout the process. Nonetheless, it was evident from observation and questioning during tutorials that the students had achieved these two outcomes through solving the Problem. The question could be changed to include a line stating, "Show that the pressure will remain constant throughout the process", which would ensure that students explained their thinking in their reports. One group did explain how the pressure would remain constant throughout the process and their answer is presented below in Box 5.2

> You may ask yourself how can we say that the pressure remains constant?
> Well, as the volume increases, the distance, d, the piston travels has an effect on the amount of molecules hitting the piston on the inside of the tube. This is because they have further to travel from the bottom of the tube where they are absorbing energy to the piston. The amount of molecules striking the piston per second becomes less than the amount of atmospheric particles striking the piston per second from the outside, but because they have a greater force than the atmospheric molecules, the pressure is steadied.
>
> momentum!
>
> per second

***Box 5.2.** Representative student answer that uses microscopic reasoning to Problem Three Part One of the PBL thermal physics module.*

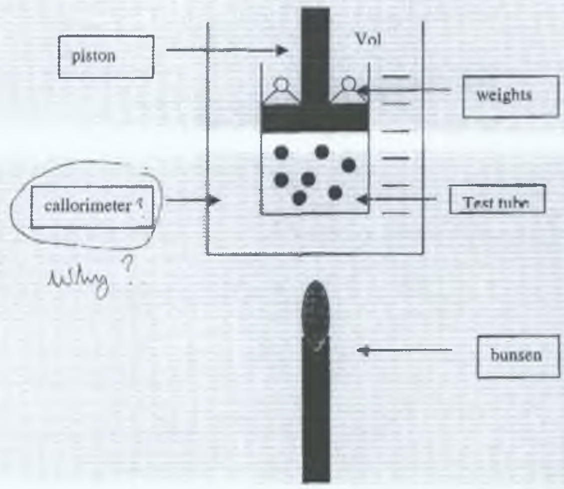
5.2.3. Comments on Part Two

We designed Part Two of the Problem to enable students to gain an understanding of constant volume processes. Students were required to determine and demonstrate the effects of adding heat to a gas, but this time it was at constant volume rather than constant pressure. As well as this, students were also asked to indicate how the pressure and temperature of the gas could be worked out after the experiment. This was to reinforce students' understanding of the relationships between the variables in the Ideal Gas Law, as well as to encourage students to transfer knowledge that they had acquired from previous Problems.

5.2.4. Students' answers to Part Two

Students found it easier to reason that pressure increases although volume stays constant than vice versa. One reason for this could be that students intuitively relate an increase in temperature to an increase in energy of the gas molecules, which when confined in the same volume produces an increase in pressure. All of the groups but one developed an appropriate demonstration and seven out of the ten explained how the pressure and temperature of the gas after the experiment could be calculated. A typical student answer to this problem is shown below in Box. 5.3

Diagram:



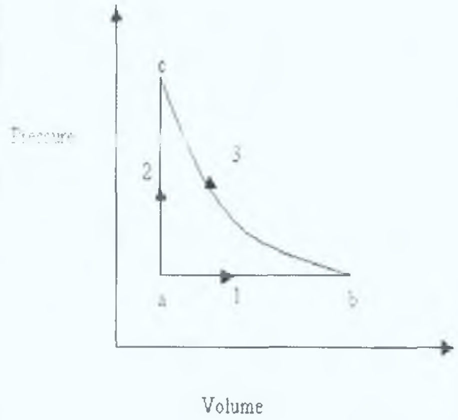
Procedure:

1. Set up apparatus as in the diagram, ensuring that the calorimeter is firmly fixed in the retort stand using the clamps provided.
2. By placing the Bunsen burner under the apparatus we can increase the temperature.
3. Note that without adding an increase in pressure the volume of the will expand, and that the volume should remain constant.
4. Using the calibrated thermocouple the temperature should be calculated and the volume should be recorded.
5. Both value's should be noted and from the previous formula the pressure can be calculated.
6. By taking different temperatures and remembering to keep the volume the same a graph of temperature(T) against pressure(P) can be drawn thus showing the relationship between T and P.

Box 5.3. *Representative student answer to Problem Three Part Two of the PBL thermal physics module.*

5.2.5. Comments on Part Three

Part three of the Problem introduces students to isothermal processes as well as to state and process variables. We developed the question so that demonstrating an isothermal process using the gas from part two would also show the difference between state and process variables; the gas would be in the same state as it was after the isobaric process, however it would have arrived there by a different path (see Box 5.4.) Thus if students carried out an isothermal expansion on the gas by releasing the piston in the test tube from part two very slowly, it would also explain the difference between state and process variables.



- Process 1 is an isobaric expansion (part one)
- Process 2 is an isochoric process (part two)
- Process 3 is an isothermal expansion (part three)
- In order to get to the final state b, you can either apply process one or both processes two & three

– The final states are the same

– Heat flow into the system is different (can show by e.g. length of time gas is heated)

– Work done is different too

Box 5.4. *p,V diagram representing the processes involved in Parts One, Two and Three of Problem Three of the PBL thermal physics module.*

It was clear from observation that students found this part of the problem difficult. All groups looked up what the term "isothermal processes" meant as their first step. However, even after research into these processes students still had difficulty in understanding them fully. Facilitators spoke to each group about this part of the problem and questioned them on their understanding of the First Law of Thermodynamics as well as isothermal processes and through this, students began to develop an understanding of these concepts.

5.2.6. Students' answers to Part Three

From the students reports it was evident that all groups had an understanding of isothermal processes and four groups also showed an understanding of how they related to the First Law of Thermodynamics (see Box 5.5 for a representative student answer). However, students did have some difficulty with state and process variables. None of the students explained how they would demonstrate the difference between state and process variables, this may indicate that this part of the question is not emphasized clearly enough, with students assuming that only an explanation of state and process variables is necessary. Four groups explained the difference between state and process variables correctly. Of the other six groups, two of them ignored this part of the question completely and the other four obtained an incorrect understanding of state and process variables from their research (see Box 5.6).

What is an Isothermal process?

An Isothermal process is one which is carried out at a constant temperature.

If an isothermal process is carried out on an ideal gas, for which PV=nRT (the Ideal Gas Law), then it follows that **PV = constant**, for a fixed number of moles(n). ✓

Note: Real gases do not follow the Ideal Gas Law precisely, however at pressures less than an atmosphere and when T is not close to the liquefaction point of the gas, the Ideal Gas Law is quite accurate for real gases. ✓

The internal energy of an ideal gas $U = \frac{3}{2}nRT$ **Eqn.3-1**

(Physics, Giancoli page 420)

Hence the change in internal energy $\Delta U = \frac{3}{2}nR\Delta T$ **Eqn.3-2**

Therefore if there is no change in temperature, then $\Delta T = 0$ ✓ and $\Delta U = 0$ ✓

Since by the first law of thermodynamics, $\Delta U = Q - W$ **Eqn.3-3**

then if $\Delta U = 0$, the heat added to the system Q, must therefore equal the work done by the system W i.e. $Q = W$

So in an isothermal process, the work done by the gas equals the heat added to the gas.

In our experiment, work is done **on** the gas, by the weight of the piston, giving a **negative** value for W. Therefore Q will be **negative**, meaning that heat energy leaves ✓ the system.

Box 5.5. *Section of students' answer to Problem Three Part Three of the PBL thermal physics module.*

State Variables are basically the property of a substance that changes automatically if you change the other properties of the substance, i.e. you have no control over it because it is a property of the substance. In this experiment the state variable can be seen, if you increase the pressure you decrease the volume. You can't stop the volume changing (because the temperature is constant).
Other examples of State Variables are

Temperature	Pressure	Volume
Entropy	Enthalpy	Internal Energy
Mass	Density	

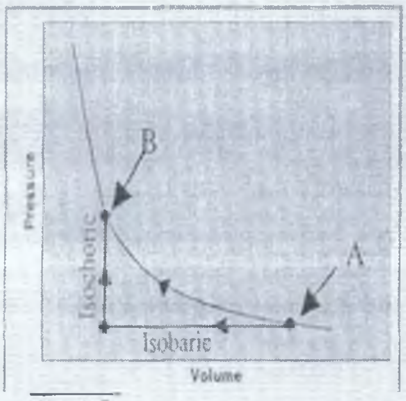
A process Variable is the opposite of a state variable. It is the properties of the substance that you have control over. In this experiment you have control over the volume, and if you decrease the volume then you increase the state variable, the pressure. ?

Therefore this experiment also shows and explains the difference between state and process variables, and also shows clearly isothermal processes for the students. ?

Box 5.6. *Section of students' incorrect answer to Part Three, Problem Three of the PBL thermal physics module.*

It is evident from the students answer above in Box 5.6 that they have not formed any understanding of state and process variables. It appears that they have copied some of their answer (lines 7,8 and 9) straight from a textbook without putting any thought into it. It became clear from this and other students answers that they were retrieving information on state and process variables in different contexts. In order to avoid this students will be introduced to the First Law of Thermodynamics before being asked to reach into state and process variables, which will provide them with a context.

Box 5.7 below shows a correct explanation of state and process variables, which was given by the students' whose explanation of isothermal processes is shown above in Box 5.5. These students display a clear understanding of how the First Law of Thermodynamics applies to isothermal processes. It is also evident that their knowledge of the First Law of Thermodynamics aided them in their explanation of state and process variables. All four of the groups who correctly explained state and process variables had explained isothermal processes in terms of the First Law of Thermodynamics, which meant that they had this in mind when researching into state and process variables. This may well indicate that in order to complete effective research into state and process variables it is necessary for students to have first studied the First Law of Thermodynamics. Other evidence in support of this can be found in the fact that the number of students able to correctly explain the difference between state and process variables (see section 5.2.9) increased after they had completed part four of the Problem, which involved the First Law of Thermodynamics.

> ΔU, Volume, Temperature and Pressure are all state variables as their value is independent of any path taken.
> Whereas W(the work done by a system) and Q(the heat added to a system) are both process variables because their value depends on the path taken.
>
> 
>
> Fig. 3-5
>
> It can be seen from Fig. 3-5 that we can change our gas from state A to state B by a different path to that taken in our practical. That is, we can achieve state B by a way of an Isobaric(constant pressure) process, followed by an Isochoric(constant volume) process.
>
> If we were to calculate the work done in each of the two different routes, by measuring the area under the graphs, we would find that the Isothermal process requires more work. Thus work is path dependant (process variable). Whereas the values for pressure and volume at point B are the constant, regardless of the path taken (state variables)

Box 5.7. Representative section of students' answer to Part Three, Problem Three of the PBL thermal physics module.

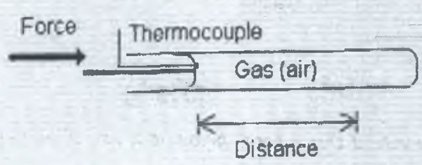
5.2.7. Comments on Part Four

We designed Part Four of the Problem to give students an understanding of adiabatic processes. We ask students to develop a demonstration that will show that temperature change can occur without heat transfer. We decided that students should not be limited to using the equipment that they have been given in part one, to provide them with more opportunity for investigation, but that anything that they do use must be readily available in a school laboratory.

Students found this part of the problem challenging; the concept of temperature change without heat transfer was new to them and something that they found difficult to comprehend. However, it was evident from observation that the Problem really encouraged discussion of the concept, with a lot of peer tutoring occurring. All students began by looking at ways that a temperature change can occur, which lead them to concept of work and the First Law of Thermodynamics. The fact that students were unrestricted when it came to equipment provided them with the opportunity to develop simple experiments, for example one group suggested showing rise in temperature with no heat transfer by stretching an elastic band and feeling it warm up.

5.2.8. Students' answers to Part Four

This part of the problem was very successful in enabling students to gain an understanding of adiabatic processes, with nine out of then ten groups developing an appropriate demonstration, and four of these explaining how the process relates to the First Law of Thermodynamics. A typical student response is shown below in Box 5.8.



When the piston is pushed down into the test tube a certain amount of work is done, i.e. the internal energy is changed. By using the thermocouple before and after pushing the piston, we can measure the change in temperature (or, the change in internal energy). The temperature after will be higher than that before. However, in order for this adiabatic process to occur, the piston must be pushed down quickly resulting in no heat transfer to the surrounds.

We can show that the work done is equal to the internal energy by using the following equation:

$$Q = \Delta U + W$$

Q	is the heat transfer
ΔU	is the change of internal energy
W	is the work done by the system

Because there is no heat transfer we can write the above equation as follows:

$$0 = \Delta U + W$$

$$\therefore -\Delta U = W$$

(ΔU is negative because work done by the system will result in a drop in internal energy.)

This change in internal energy corresponds to a change in temperature as internal energy is the sum of all kinetic and potential energies of the particles of the gas, and we know that a rise in kinetic energy results in a rise in temperature.

Box 5.8. Representative student answer to Problem Three Part Four of the PBL thermal physics module.

5.2.9. Comments on Part Five

We based the final part of the problem on a theoretical rather than practical question. It is a short question designed to enable students to develop an understanding of state and processes variables in relation to the First Law of Thermodynamics. Six out of the ten groups demonstrated an understanding of the differences between state and process variables and the fact that as heat and work are process variables it is impossible to determine them from state quantities, (see Box 5.9 for a typical student answer).

There was an increase in the number of students giving a correct explanation of state and process variables compared to part three of the Problem. As every group that correctly answered part five of the Problem explained how state and process variables relate to the First Law of Thermodynamics it suggests that it is beneficial for students to have studied this Law at the same time as they are attempting to understand state and process variables. It may be advantageous to rearrange the Problem and present students with Part Four before Part Three. As most students researched into the First Law of Thermodynamics when studying adiabatic processes, this would ensure that students had encountered this Law before being introduced to state and process variables.

> In the group's opinion, if you are given the initial state function and the final state function but are not given the path functions you cannot tell how the system came about the changes in the state function.
>
> If for instance you are given the equation
>
> $$\Delta U = Q + W$$
>
> ΔU is the change in internal energy
> Q is the heat applied
> And +w is the work done on the system
>
> - The state function in the equation is ΔU
> - The path functions in the equation are Q and +w.
>
> So Q and +w can change but ΔU might not. But if the heat-applied (Q) was to change and the work by the system (+w) was to stay constant then the internal energy would change. But also if the work on the system was to change and the heat applied (Q) was to stay constant then the internal energy would also change.
>
> Therefore if you are given the initial and final state functions then you cannot decide what path function it was that changed.

Box 5.9. *Representative student answer to Problem Three Part Five of the PBL thermal Physics module.*

5.3. Assessment of students' understanding of the First Law of Thermodynamics

5.3.1. Pre test for Problem Three

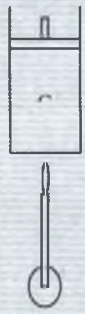
We used a test from a paper written by Rozier and Viennot[1], who report on students reasoning in thermal physics, as the pre test, so that we could compare our results with those reported. This test assesses students' ability to apply the Ideal Gas Law and involves multiple variable reasoning. We chose this particular question because it simultaneously serves as a post test to Problem Two and it allowed us to assess if the Problems had any effect on students ability to deal with multiple variable relationships, as compared to the findings reported by Rozier and Viennot. We altered the question slightly by asking students to predict as well as explain the effect of heating a gas at constant pressure because we felt that it would provide us with a better understanding of students reasoning. The pre test is shown below in Box 5.10.

Pre Test

An ideal gas is contained within a cylinder with a tightly fitting piston.

The gas is then heated at constant pressure.

What happens to the temperature and volume of the gas? Explain.



Box 5.10. *Pre test given to students before thermal physics Problem Three*[1].

5.3.2. Assessment objectives of the pre test

The pre test assesses students' ability to apply the ideal gas law to an isobaric process. A representative correct answer is presented below in Box 5.11.

- *The ideal gas law applies as the gas is at low pressure and high temperature*
- *The gas is heated and $c_p>0$, so the temperature rises*
- *Because pressure and number of moles are constant, the volume must increase*

Box 5.11. *Representative correct answer to the pre test given before Problem Three of the PBL thermal physics module.*

In order to answer this question students firstly need to recognise that the Ideal Gas Law is applicable. Questions involving the Ideal Gas Law require, in principle at least, multivariable reasoning, as p, V, n, and T are all interdependent. In this case however p and n are constant, there must be an increase in volume when the temperature increases.

5.3.3. Post test for Problem Three

We used a test from a paper written by Loverude *et al* [2], as a post test for Problem Three so that we could compare our findings with those reported. The question we chose was based on the adiabatic compression of an ideal gas. The reason that we chose this particular question was because it cannot be answered using the Ideal Gas Law alone, it requires the use of the First Law of Thermodynamics. The fact that the Ideal Gas Law alone cannot be used to answer the question assesses students' ability to deal with multivariable reasoning. Students can deduce from the Ideal Gas Law that the product of pressure and volume is increasing, however it is not possible to tell what's happening to the individual variables unless the effect of temperature is known, which requires the use of the First Law of

Thermodynamics. One of the learning outcomes of the problem (see appendix A) was that students would develop an understanding of and be able to apply the First Law of Thermodynamics. As the pre test was based on the Ideal Gas Law, we felt that this particular question would be ideal as it would enable us to assess the effect of the Problem on students understanding of the Ideal Gas Law as well as their ability to recognise the relevance of and apply the First Law of Thermodynamics. The post test is presented below in Box 5.12.

An ideal gas is contained in a cylinder with a tightly fitting piston.

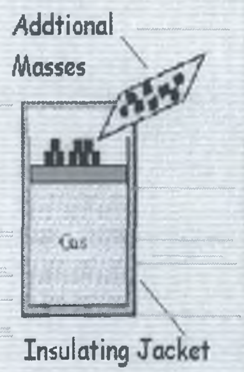
Several small masses are on the piston.

(Neglect friction between the piston and the cylinder walls)

The cylinder is placed into an insulating jacket.

A large number of masses are added to the piston.

Will the pressure, temperature and volume of the gas increase, decrease or remain the same. Explain.



Box 5.12. *Post test given to students after they completed Problem Three of the PBL thermal physics module.*

5.3.4. Assessment objectives of the post test

As pressure increases and volume decreases the Ideal Gas Law cannot be used to predict what happens to the temperature. Students must realise that the First Law of Thermodynamics is applicable and from this determine that there is an increase in temperature. A representative correct answer to the post test is shown below in Box 5.13.

- *Weight on piston increases so the pressure increases*
- *Net force on piston, it moves down*
- *Gas volume decreases*
- *Work is done on the gas*
- *No heat escapes*
- *Internal energy increases so the temperature increases*

Box 5.13. *Representative correct answer to the pre test given after Problem Three of the PBL thermal physics module.*

5.4. Comparison of our findings with the literature

5.4.1. Comparison of the findings of Rozier and Viennot with our pre test results

Rozier and Viennot[1] found that incorrect linear reasoning was very common (43% N=120). They explained the increase in temperature and volume by applying the Ideal Gas Law in a two-step process:

1. Heating results in a temperature increase and thus pressure increases (implicitly holding the volume constant)
2. As the piston is free to move, the volume increases

Students don't see this as contradictory, even though the question states that the pressure is constant as they view the processes as happening in steps over time. This type of reasoning was evident in our students' responses to the pre tests (see Table 5.1). A common (30%) student error was to apply Boyle's Law. This is surprising as it is only applicable at constant temperature, however all of those students that applied it, showed incorrect linear reasoning by applying it (implicitly holding the temperature constant) and then stating in the next step of the process that the temperature increases.

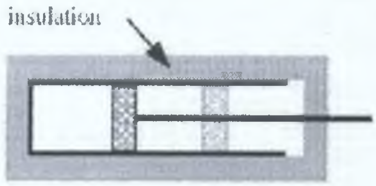
	1st Years	2nd Years
Correct answer and explanation for volume	9%	36%
Correct answer and explanation for temperature	74%	100%
Correct answer with reasoning not clearly explained	26%	21%
Show inability to deal with multivariable relationships	35%	36%
Applying Boyle's Law	30%	0%
Stating Ideal Gas Law	30%	79%
Applying Ideal Gas Law incorrectly	13%	0%

Table 5.1. *Results from the Pre Test on students' ability to recognise the relevance of and apply the Ideal Gas Law.*

5.4.2. Comparison of the findings Loverude of et al with our post test results

Loverude *et al's* study involved two different questions based on the same concept. One of the questions was the one that we used as our post test. The other was a written version of a problem based on a bicycle pump and is shown below in Box 5.14. As Loverude *et al* only give the results of students' answers to this question, this is what we have compared our results to (see Table 5.2.) The only major difference between the two questions is that the first question requires students to determine what happens to the pressure and volume whereas the bicycle pump question does not.

A cylindrical pump contains one mole of an ideal gas. The piston fits tightly so that no gas escapes, but friction is negligible between the piston and the cylinder walls.



a. Version A	b. Version B
The pump is thermally isolated from its surroundings. The piston is quickly pressed inward as shown. ***What will happen to the temperature of the gas? Explain your reasoning.***	The piston is quickly pressed inward as shown. A sensor in the pump records an increase in temperature. ***How can you account for the increase in internal energy of the gas? Explain your reasoning.***

Box 5.14. *Bicycle pump problem administered by Loverude et al to assess students understanding of the First Law of Thermodynamics.*

Loverude *et al* administered the tests to students from a range of different courses. We make a comparison between the answers of Loverude *et al's* first and second year students with our Science Education and Physics students' answers. Loverude *et al's* first year students were enrolled in a large algebra based physics course and their second years were completing a thermal physics module. The number of correct responses that our students gave was less than Loverude *et al's* (see Table 5.2); but the amount of correct explanations based on work were approximately the same. This is perhaps not surprising, since the question posed by Loverude *et al* dealt with temperature only, whereas our students needed to consider pressure and volume as well.

	Loverude et al (Post)		Our Findings (Post)	
	1st Years	**2nd Years**	**1st Years**	**2nd Years**
Correct responses (T increases)	67%	86%	57%	44%
Correct explanation based on work	10%	25%	10%	22%
Incorrect explanation	57%	35%	47%	22%
Incorrect responses	33%	14%	33%	33%

Table 5.2. *Post Test results on students' ability to recognise the relevance of and apply the First Law of Thermodynamics.*

Loverude *et al* found several types of incorrect explanations similar to those of Rozier and Viennot, which we also found to be present. (see Table 5.3). The most common error, made by 50% of our students was to implicitly hold one variable constant and thus to assume an invalid relationship between another two. It appears that students incorrectly held variables constant to allow them to apply the Ideal Gas Law, where the First Law of Thermodynamics would have given the necessary constraints.

Loverude *et al* and Rozier and Viennot also discovered that students had incorrect microscopic ideas, particularly regarding the relationship between number density and gas temperature. We also found this to be the case, with students explaining the increase in temperature as a result of the gas particles being compressed into a smaller volume, resulting in more collisions, which the students stated would produce heat. At this stage of the module, students had no formal instruction in the microscopic properties of the gas particles; consequently we found it surprising that so many (see Table 5.3) applied this type of reasoning in the pre and post tests. These incorrect microscopic ideas lead to misconceptions; for example 13% of students made the surprising mistake of saying that temperature was inversely proportional to volume, which, even under the assumption of constant pressure doesn't hold. Loverude et al report a similar number for this error.

Responses	**1st Years**	**2nd Years**
Correct answer and explanation for all	5%	0%
Correct answer and explanation for volume	29%	56%
Correct answer and explanation for pressure	57%	56%
Correct answer and explanation for temperature	10%	22%
Incorrect microscopic ideas (friction causing heat)	10%	33%
Stating the process is isothermal (temperature actually increases)	15%	22%
Inappropriate linear reasoning (holding temp constant then stating it increases) (holding volume constant then stating it decreases)	30%	56%
State Ideal Gas Law	19%	56%
State first Law of thermodynamics	14%	22%

***Table 5.3.** Common incorrect responses to the Post Test on students' ability to recognise the relevance of and apply the First Law of Thermodynamics (Box 5.12).*

The results of the post test indicate that students still have difficulty in seeing the relevance of the First Law of Thermodynamics to this type of problem. This was also somewhat evident in the final exam, (see section 5.5.1)

5.4.3. Conclusions from pre and post tests results

The pre test was effective in determining students' ability to apply the Ideal Gas Law and so was appropriate as a post test for Problem Two. It is clear from students' answers to the pre test that Problem Two was successful in developing their ability to apply the Ideal Gas Law. However, the fact that the post test was more complex in some aspects meant that the effect of Problem Three couldn't be assessed by direct comparison. As students have no previous knowledge of the First Law, rather than making the pre test more complex, it would be better to make the post test simpler. If the post test only required the use of Ideal Gas Law, but in a different context to the pre test then the affect of the Problem on students understanding could be more accurately determined. However, this would be at the expense of assessing the effect of the Problem on developing students understanding of the First Law of Thermodynamics and the effect is had on furthering their knowledge of the Ideal Gas Law.

5.5. Assessment of students' understanding of thermodynamic processes

5.5.1. Introduction

Question Two of the exam paper assessed students' understanding of the Ideal Gas Law and the First Law of Thermodynamics. As a result, students' answers to it can give us some indication of the effect that Problem Three had on their understanding of these concepts. The question is a standard question similar to an end of chapter question, partly to assess if students could answer non-PBL questions, and is presented below in Box 5.15.

Question 2

You have 0.0135 moles of gas inside a test tube whose axis is vertical. The tube is closed off by a piston that fits tightly but can move without friction. There is no insulation around the test tube. The temperature of the gas is initially 20 °C, and its volume is 300 cm^3. You then heat the test tube with a Bunsen burner and observe that the piston rises.

a) Evaluate the initial pressure. State and justify the assumptions you make.
b) Can you predict if the temperature of the gas will increase, remain the same or decrease while the Bunsen burner is on? Explain your answer.

When you take the Bunsen burner away, the volume of the gas has increased to 324 cm^3.

c) How much work has been done by the expanding gas?
d) If the change in internal energy of the gas is 7.0 J, what is its relevant specific heat?
e) How much heat has been added to the gas?

Box 5.15. *PBL thermal physics module final exam Question Two.*

5.5.2. Comments on part a and b

Parts a and b of the exam question are similar to the pre test (see Box 5.10). In the pre test students are asked to explain what will happen to the temperature and volume of a gas heated at constant pressure and not insulated whereas in the exam question this is the other way around. Both questions test students' ability to apply the Ideal Gas Law. Comparing the results of student answers to the exam question (see Table 5.4), with those of the pre test (see Table 5.1) there is evidence of an improvement in students' ability to apply this Law. Firstly, no students applied the Ideal Gas Law incorrectly when answering part a of the exam question, compared to 13% of students in the pre test. As well as this, 55% of students failed to recognise the relevance of the Ideal Gas Law to answering the pre test compared to 34% of students in the final exam. From this we can conclude that students' ability to recognise and apply the Ideal Gas Law was improved to some extent through their completion of Problem Three and Five, as they completed these Problems, which involve the Ideal Gas Law, after the pre test and before the final exam.

Part a of the question was straightforward, students were required to state the assumption that the gas was in equilibrium with its surroundings, as well as those assumptions they were making in using the Ideal Gas Law. Students then had to manipulate the equation and substitute in values to calculate the pressure. One third of the students answered this part of the question completely correctly. Although this percentage is low, the most common mistakes were numerical errors and didn't reflect on students' understanding of the concepts involved. The most frequent errors were not converting volume to metres cubed correctly (39% of students), or substituting temperature in Celsius rather than Kelvin (27% of students).

Just over half the students (55%) answered part b of the question correctly using the Ideal Gas Law, they reasoned that, as pressure is constant, and volume increases, the temperature must increase.

5.5.3. Comments on part c, d and e

As well as assessing students' ability to make assumptions, and their understanding of physical concepts, we also wanted to assess their ability to perform numerical calculations, as it is a skill that they require. Parts c, d and e of the question assess this skill. The main difficulty that students had with these questions, was not knowing the formulae that were required; this was particularly apparent in answers to parts c and d.

Part c caused students some difficulties as they were not able to recognise the relevance of, or remember the expression for, work in an isobaric process and so could not perform the calculation. For part d of the question the major difficulties were once again caused by a lack of knowledge of the formula. In order to calculate the specific heat of the gas, students needed to realise that it was the molar specific heat that was relevant, $Q = n.C_p.\Delta T$. Most students didn't attempt to answer the question, with 53% leaving it blank. Those students that did attempt it, used a mass related specific heat, $Q = m.c.\Delta T$. As they were able to calculate both the change in temperature and the heat added, they were able to give the specific heat capacity of the gas in terms of mass. Although these students didn't know the required formula, that involving the molar specific heat, they did recognise the concepts involved and were able to attempt the question.

The key to answering part e of the question was recognising the relevance of the First Law of Thermodynamics. Once students did this, they could easily calculate ΔQ. There are two contributions to Q, the heat in (from the Bunsen burner) and the heat out (through the walls of the cylinder). However, students were not required to make this distinction and if they just calculated the net Q, they were eligible for full marks regardless of whether they did so or not.

The main difficulty with this question was that if students did not recognise the relevance of the First Law of Thermodynamics, they were unable to answer it. This was evident from the student answers to the question; 50% of them did recognise the relevance and completed the calculation. However most of those students who didn't recognise the relevance never attempted the question, with 43% of students leaving it blank. The fact that students had difficulty recognising the relevance of the First Law to this question, indicates that they have difficulties with knowing when to apply it. Loverude *et al*, also found that their students had this difficulty. They report that many of their students were unable to recognise the relevance of or apply the First Law of Thermodynamics. They also found that students were most likely to try and use the Ideal Gas Law and seemed to consider this the equation of major importance from the course they had studied. As our students dealt with the Ideal Gas Law in Problems Two, Three and Five and only dealt with the First Law of Thermodynamics in Problem Three, they also may have felt that the Ideal Gas Law was the most important equation from the course. They may also have felt that the First Law of Thermodynamics was relevant to fewer situations and this may explain why only half the students thought of this law when answering part e of the question.

5.6. Conclusion

It was evident from the pre test results that students had gained an understanding of the Ideal Gas Law, as well as an ability to apply it from Problem Two. During tutorials there was evidence that Problem Three improved this skill, as students were applying it to determine the effects of heating a gas at constant pressure and at constant volume. The fact that the post test showed that students' misconceptions about the relationship between volume and temperature were eradicated also demonstrates that their understanding of the Ideal Gas Law and ability to relate the variables has improved.

It was evident from students reports on Problem Three that if they applied the First Law in thinking about isothermal processes in Part Three, then they were more likely to correctly explain state and process variables. In order that more students are successful in developing an understanding of state and process variables and gaining a deeper understanding of the First Law it may be beneficial to change the order of the Problem so that Part Four comes before Part Three. In this way, students will have looked at the First Law before they study isothermal processes and state and process variables. It will also ensure that the First Law features in the final three parts of the Problem and so it may seem more significant to the students. However, those students that did recognise the relevance of the First Law to the questions were able to apply it and so the Problem was successful in this. However, the importance and relevance of the First Law needs to be emphasised more.

References:

1. S. Rozier and L. Viennot, *"Students' reasonings in thermodynamics"* International Journal of Science Education 1991, Volume 13, No.2, 159-170
2. M. Loverude, C. Kautz and P. Heron 2002 *"Student understanding of the first law of thermodynamics: Relating work to the adiabatic compression of an ideal gas"* American Journal Physics Volume 70 Issue 2, 137-148

Chapter Six Discussion of Problem Four

6.1. Introduction to Problem Four

Problem Four is presented in Box 6.1 on the next page. We designed this Problem to introduce students to the Second Law of Thermodynamics as well as to the concept of engine efficiency and the Carnot cycle. As students have no background knowledge, research into these topics is challenging, so we made the questions uncomplicated. The only change we made to this Problem before the second delivery was to alter part two to read "coefficient of performance" instead of "efficiency" in relation to a refrigerator, as this is the term used in the textbooks.

6.2. Students' response to Problem Four

6.2.1. Comments on Part One

Part one of the Problem provides an introduction to the context of the Problem, reinforces concepts that students have studied in Problems One and Two and introduces the concept of latent heat. In order to successfully answer the question students must model the heat flow into the cool box, making valid assumptions and simplifications as they do so. Students had previously modelled heat flow in Parts Two and Three of Problem One and in Part Three of Problem Two.

During tutorials, it was evident that students were using their knowledge from Problem One in solving this part of Problem Four. For example, one student told the other group members that they shouldn't use thermal conductivity to model the heat transfer. She reminded them about the build up of an insulating air layer on either side of the cool box and that the U value would be more suitable as it takes this into account it. Students were expanding the modelling skills that they had begun to develop through applying them to a familiar concept (heat transfer) in a new situation.

Thermal Physics – Problem Four

Part One

Bob and some of his friends are going on a fishing trip on the South coast. They are going for 3 days, so they want to bring a cool box in which to keep what they catch. Decide on the volume of the cool box and estimate how much ice you would need to fill it with to keep the otherwise empty cool box at 0°C for this time.

Part Two

On somebody else's boat, Bob and his friends have noticed a cooler unit placed on top of a cool box. The cooling unit doesn't run too hot: it's warm to the touch, but doesn't burn the skin. They consider buying such a system and find that the price wouldn't be prohibitive. Bob's friends worry about the energy consumption and ask Bob to work out how much energy would be drained from the boat's batteries.

Bob does some research and finds out from the manufacturer that the cooling unit runs at 43% of the theoretically attainable coefficient of performance at these temperatures. In order to find out how much energy would be drawn from the batteries, Bob estimates how much heat enters the empty cool box from the outside and from that works out how much energy needs to be drawn from the batteries. Try and repeat Bob's calculations. Why is it best to place the cooling unit on the top of the box?

Part Three

Bob reckons optimistically that they will be able to catch 70 kg of fish. They store the fish in the cool box so they can bring it home to eat. They want to keep the fish frozen. How much energy needs to be drawn from the batteries in this case?

Box 6.1. *Problem Four of the PBL thermal physics module.*

6.2. Students' response to Problem Four

6.2.1. Comments on Part One

Part one of the Problem provides an introduction to the context of the Problem, reinforces concepts that students have studied in Problems One and Two and introduces the concept of latent heat. In order to successfully answer the question students must model the heat flow into the cool box, making valid assumptions and simplifications as they do so. Students had previously modelled heat flow in Parts Two and Three of Problem One and in Part Three of Problem Two.

During tutorials, it was evident that students were using their knowledge from Problem One in solving this part of Problem Four. For example, one student told the other group members that they shouldn't use thermal conductivity to model the heat transfer. She reminded them about the build up of an insulating air layer on either side of the cool box and that the U value would be more suitable as it takes this into account it. Students were expanding the modelling skills that they had begun to develop through applying them to a familiar concept (heat transfer) in a new situation.

6.2.2. Students' answers to Part One

Most students started by thinking about what would happen to the ice once it was placed into the cool box, and decided that it would melt due to heat entering the box from outside. This then led them to think about phase changes and introduced them to latent heat. Once students had established that this was the relevant concept they had no difficulties applying it to calculate the mass of ice required. One of the more challenging aspects of the problem for students was modelling the heat flow into the cool box and assessing what assumptions and simplifications they needed to make. All groups but one concentrated on modelling heat transfer through conduction. There was evidence of students transferring their knowledge from Problem One, with eight of the ten groups using U values rather than thermal conductivity values when calculating the heat flow into the cool box. Eventually, all groups decided that they would assume a constant average outside temperature and that the inside of the cool box was at 0°C when the ice was placed inside and managed to calculate the heat flow into the cool box over the three days. A typical student answer to this part of the problem is shown below in Box 6.2.

The energy in this case is going to be supplied from the environment outside the cooler. To find how much ice Bob needs to take with him we can calculate the heat that is being absorbed by the cooler box in three days. Then by making that equal to the energy used in the change of state, or fusion, of the ice we can find the mass of the ice needed from the formula

$$Q = m\,L_{fusion} \qquad (1)$$

Where Q = energy used in fusion (Joules)

m = the mass of the ice (kg)

and L_{fusion} = the specific latent heat of fusion = 330(KJ/kg) $_{source3}$.

Firstly we must find the energy being absorbed by the box. To do this we can use the formula

$$E = U_{-value}\,A\,\Delta T \qquad (2)$$

Where E = conducted energy (watts)

U_{-value} = U-Value of polystyrene (W/m^2/K)

A = Area (m^2)

and ΔT = Temperature difference on either side of walls (K).

<u>Assumptions:</u>

1m^3

- The box has an internal volume of 1m^2 and is made of 3cm white moulded polystyrene, which has a Thermal conductivity of 0.13 W/m/K $_{source1}$ and 1cm rigid uPVC, which has a thermal conductivity of 0.19 W/m/K $_{source7,\ source1}$.
- The internal temperature of the cooler box, with the ice in it, is a constant 0°C.
- The external temperature is also constant at 8°C $_{source2}$.
- There are no other forms of heat transfer considered except for conduction. why?
- There is 50% less heat loss through the surface of the box resting on the deck of the boat.

And finally the total U-Value of the cooler box is

U-Value = 1 / 2.834

= 0.35 units!

Now not forgetting that one side of the box absorbs 50% less heat than the rest,

From equation (2) E = (0.35 x 5 x 8) + ½(0.35 x 1 x 8)

⇨ E = 14 + ½(2.8)

⇨ E = 17.6 + 1.4

⇨ E = 19w

Then, E_{tot} = 19 (W) x 60(seconds) x 60 (minutes) x 24 (hours) x 3 (days)

= 4,925 kJ.

Now making E_{tot} = Q from equation (1) we get

4,925 = m (330)

⇨ m = (4,925 / 330)

⇨ m = 14.92 kg of ice.

Box 6.2. *Representative student answer to Problem Four Part One of the PBL thermal physics module.*

As can be seen from these students answer, Part One of the Problem helped students develop their skills of making appropriate assumptions. Although these students calculated the heat flow into the cool box using U values, which is something that they had done before, they first had to simplify the physical model of the situation. This part of the Problem made students consider which form of heat transfer was most relevant, conduction, convection or radiation. They also had to make appropriate estimations of the temperature inside and outside the cool box and consider if they could assume that these temperatures were constant without affecting their calculations. These students also thought about the environmental factors when modelling the heat flow into the cool box, which is evidenced by the fact that they estimate that the part of the cool box in contact with the boat absorbs 50% less heat than the other five sides.

It is also evident from these students' answer to Part One of the Problem that it was successful in enabling students to develop an understanding of latent heat. These students recognise that it is latent heat that is applicable as the ice is changing state and there was further evidence from their answer that they had completed research into the topic, as they give an explanation of it.

6.2.3. Comments on Part Two

We developed Part Two of this Problem to provide students with the opportunity to research into the Second Law of Thermodynamics, heat engines and the Carnot Cycle. The calculations involved in this part of the Problem are not very complex; they involve calculating the coefficient of performance of a refrigerator and from this estimating the power used by the refrigerator. However, developing an understanding of the concepts involved is quite difficult, particularly as they are completely new to the students.

Another aspect to this part of the problem was that students had once again to model the heat flow into the cool box. They had to make different simplifications and assumptions, to take into account the cooling unit, such as, that it's in thermal equilibrium with the top of the cool box. It was evident from observation during tutorials that as students had already modelled heat flow into the cool box in Part One of the Problem, they had less difficult in determining which assumptions and simplifications were necessary for Part Two.

6.2.4. Students' answers to Part Two

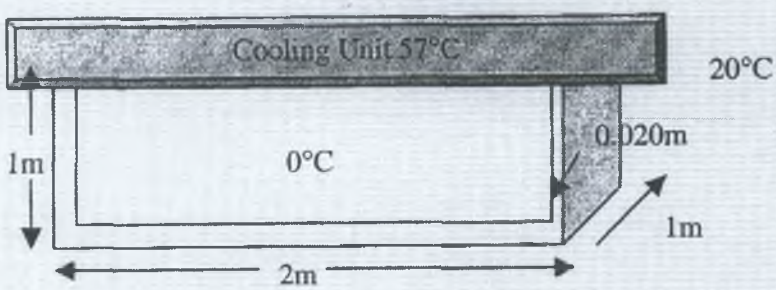
Most groups started by looking up the term "coefficient of performance" (CP), as it was new to them. This then led them to discover the Second Law of Thermodynamics and heat engines. The next step was to learn that theoretically attainable efficiency meant the maximum efficiency theoretically possible which led them to the Carnot cycle. Students did find this part of the problem challenging, even though they knew from the question that they needed to look up co-efficient of performance, once they'd done this they had difficulty understanding what it meant. Most students thought that they had developed a complete understanding of the Second Law and when questioned explained that it made sense that work was necessary to make heat flow from a cold to a hot body. However, when it came to applying this concept, as with heat engines, students had difficulties. The most common problem was with the concept of efficiency and understanding why the Carnot cycle represented the most efficient engine or refrigerator possible.

Seven out of the ten groups successfully answered this part of the problem. A typical student answer is shown below in Box 6.3. These students start off by modelling the heat flow into the cool box again to take into account the changes have occurred since Part One. They then go on to demonstrate that they have carried out research into refrigerators and the Second Law, giving a reference to a textbook. Finally the students use the knowledge that they have gained to calculate the CP of the cooling unit and from this estimate the drain on the boats batteries.

Part 2

How much heat energy enters the empty cool-box from the outside.

Figure 1 *Dimensions of Bob's cool-box with cooling unit installed*



As in part one the heat that is lost from the cool-box must be calculated. In this setup however there are only 5 sides that are in contact with the outside air while the sixth is in contact with the cooling unit. New dimensions for area and temperature difference must be considered. The cooling unit is warm to touch so we have assumed that it is at 57°C.

Therefore the total heat loss (H_T) out of the cool-box is;

5.

$$H_T = H_1 + H_2$$
$$H_T = (80W) + (57W)$$
$$H_T = 137W$$

The cooling unit operates by transferring heat out of the colder cool-box into the warmer outside environment. There is no such thing as a perfect refrigerator i.e. one which can take out all the heat from the cold regoin to the hotter region without doing any work. This is, according to Giancoli's *Physics (fifth edition)* is known as '*the Clausius statement of the Second Law of Thermodynamics.*' It is a part of nature that heat flows from hot to cold. It is not possible for heat to flow from a cold to a hot object without some work being done. There is however, an ideal refrigerator which we have assumed is the case for our cooling unit in this problem. The CP of our cooling unit (the coefficient of performance) is the heat taken out of the cool-box divided by the work necessary to remove it. This gives us the following formula;

6. $$CP = \frac{Q_l}{W}$$ ✓

where CP = Coefficient of performance
Q_l = Heat removed from cool-box
W = Work done in removing heat

9. $$CP = \frac{Q_l}{Q_h - Q_l}$$ ✓

Since Bob's cooling unit is an ideal refrigerator, according to Giancoli's Physics (fifth edition), this can be rewritten as;

10. $$CP = \frac{T_l}{T_h - T_l}$$ ✓

where T_l = Temperature inside the cool-box (0°C = 273.15°K)
T_h = Temperature of cooling unit (57°C = 330.15°K)

Therefore we found that the CP of Bob's cooling unit was

$$CP = \frac{(273.15°K)}{(330.15°K) - (273.15°K)}$$
$$CP = 4.792$$

But Bob found out from the manufacturer that the cooling unit was running at 43% of the theoretically attainable coefficient of performance. So the CP of the unit was

$$CP = \frac{43}{100} \times 4.792$$
$$CP = 2.06$$ ✓

11. $W = \frac{Q_l}{CP}$

$W = \frac{(137W)}{(2.06)}$

W = 66.5Watts or 66.5J/s ✓

Over three days this is a total energy drainage (W_t) from the batteries of Bob's car of;

$W_t = (66.5J/s)(86400s)(3)$

Units of seconds cancel and we are left with an answer of

$W_t = 17236800J$
$W_t \approx 17MJ$

Why is it best to place the cooling unit on top of the box?

It is best to place the cooling unit on top of the box due to the fact that ~~heat~~ hot air rises. Consequentely placing the unit on top of the box will ensure that all heat inside the box will rise and as a result be processed and cooled. ✓

Box 6.3. *Representative student answer to Problem Four Part Two of the PBL thermal physics module.*

The three groups that failed in solving the problem correctly did so because they failed to develop a full understanding of the Second Law of Thermodynamics and heat engines. One of the incorrect answers is shown below in Box 6.4. As can be seen from these students' answer, they have not thought about engine efficiency or the Second Law of Thermodynamics at all in completing the question. This was the extreme however. The other two groups that didn't successfully answer the question, did research into coefficients of performance, however they didn't develop a correct understanding of the concept. Both of them failed in understanding how the Problem related to the Carnot cycle and assumed that the CP of the cooling unit was forty three per cent.

But we are told in the second part of the question that *"the cooling unit runs at 43% of the theoretically attainable co-efficient of performance at these temperatures"*.

needs to be looked up

$cp = \frac{Q_L}{W}$.

This means that for the cooling unit to output the 59.693 joules per second or Watts, then more power needs to be taken from the battery to do that. I.e. the heat that needs to be cooled is only 43% of the energy taken from the battery. That means that we now must calculate the value of the power taken from the battery in order to replace the 60 watts of heat energy that is coming in from convection and radiation.

$$\frac{43}{100} = \frac{60}{x}$$

$$6000 = 43x$$

$$x = 138.8 watts$$

Which means that nearly 140 watts of energy is taken from the battery per second. Its not a substantial amount of energy, its about the same energy needed to power about two 60 watt light bulbs. But given that the engine of the boat will be running most of the time, then the battery on the boat should recharge itself like all other vehicles, meaning that the cooling unit is perfectly viable for the boat given the assumptions made.

Box 6.4. *Representative incorrect student answer to Problem Four Part Two of the PBL thermal physics module.*

In relation to the other two groups who failed to answer the question correctly, it is clear from observation notes written after the tutorial session (see Box 6.5), that both groups had started researching into the required concepts, however when it came to applying them, it became evident that they hadn't developed a correct understanding.

These students had also begun to look at part two. One of them, who had previous knowledge of the working of refrigerators had drawn a diagram and was explaining it to the other students who weren't as sure. It was a very good example of how PBL can be beneficial and encourage discussion and peer tutoring. Another student from the group was looking at coefficients of performance and they were really questioning what assumptions they could make, how the heat flow into the colder area was related to the temperature of the heat pump and striving to develop an in-depth understanding.

Box. 6.5. *Observation notes on students approach to solving part two of Problem Four.*

6.2.5. Comments on Part Three

The final part of the Problem further develops students' understanding of latent heat, specific heat capacity and heat transfer. Students need to calculate the initial heat removed to freeze the fish, which involves using the specific heat capacity and latent heat equations (see Box 6.6). Then students must calculate the heat flow into the cool box on the journey home, as this must also be removed to ensure the fish remain frozen. Solving this part of the Problem encourages students to think once more about heat transfer and what assumptions and simplifications they can make in calculating the heat flow into the cool box. Students have to consider the best method of calculating heat flow through conduction and so the concept of thermal transmittance as opposed to thermal conductivity, once again comes into question, in this way the Problem builds on what students have learned from Problem One, Part Three (see section 3.2.4.) In solving this problem, students develop an understanding of the differences between the formulae involved, which they have seen before in Problem One, Part Two (see section 3.2.2.) This is something that did cause students confusion initially when they solved Problem One, particularly confusing the temperatures involved in the equations. Working through this question reinforces the fact that the temperature difference in the specific heat equation is that of the same body at two different times, whereas that in the thermal conduction formula is the difference in temperature between two bodies at the same time. This part of the Problem also develops students' ability to determine which concepts and equations are applicable to different situations.

Heat removed in cooling the fish to 0°C	$Q = m.c.\Delta T$	(1)
Heat removed in freezing the fish	$Q = m.c.\Delta T$	(2)
Heat removed in changing the state of the fish	$Q = m.L_f$	(3)
Heat removed to keep the fish frozen	$Q = U.(T_h\text{-}T_c).A$	(4)

Box 6.6. *Formulae required to solve part three of Problem Four of the PBL thermal Physics module.*

Part Three of the Problem also involves calculating the coefficient of performance and estimating the energy drawn from the boats batteries and consequently reinforces what the students had learned from Part Two by providing them with an opportunity to further develop their understanding of the topics involved.

6.2.6. Students' answers to Part Three

Although students had already studied the concepts needed to solve this part of the Problem, they had some difficulties in determining the best way to approach it and in taking into account all the relevant factors. Most of the groups calculated three out of the four amounts of heat that needed to be removed from the cool box. Another common mistake was for students to use the CP that they had calculated in part two, although this wasn't appropriate, as the cooling unit was operating at different temperatures. Half the groups calculated the drain on the boats batteries. A typical answer is presented below in Box 6.7

The assumptions for this part of the problem are;

- When the fish are caught, their temperature is 5°C (278K)
- The fish are cooled from 5°C to –18°C very quickly, so that the time taken to do this is negligible compared to 3 days (*see note below)
- In order to keep the fish in a frozen state they must be kept at a temperature of -18°C (255K)
- The outside temperature is a constant 10°C

There are three stages to this calculation;

1. First we need to calculate the heat energy removed from the cool box to reduce the temperature of the fish from 5°C to –18°C. We will call this heat energy Q_1
2. Then we calculate the heat energy removed from the cool box to bring the fish from –18°C(liquid phase) to –18°C(solid phase). We will call this heat energy Q_2
3. Finally we calculate the heat energy removed from the cool box to keep the fish frozen at –18°C for three days. We will call this heat energy Q_3

Adding these three heat energy quantities will give the total heat energy removed from the cool box, by the cooler unit, to keep **70kg** of fish frozen for three days.

To calculate the total heat energy removed by the cooler unit for part 3 of the problem we add Q_1, Q_2 and Q_3

Giving $Q_{total} = 5586.7kJ + 23401kJ + 12700.8kJ = 41688.5kJ$

Using Eqn. 6 we can calculate the work done by the batteries in order to provide 41688.5kJ of energy.

But CP will be different as its at different temperatures.

In Part 2 we calculated the coefficient of performance CP, of our engine to be 2.93

This gives a value for $W = \frac{Q_{total}}{CP} = \frac{41688.5kJ}{2.93} = 14228.157kJ$

Note: The units for work are usually given as Js^{-1}, but the value used for Q_{total} in our calculation is actually the total energy used in three days, not the energy used per second.

← Power

J

$CP_{ideal} = \frac{T_C}{T_H - T_C} = \frac{255}{58} \approx 4$

$CP = 2$

Thus the total energy required from the batteries over three days, to provide enough energy to keep 70kg of fish frozen at –18°C is **14228.157kJ**

Too many s.f.

Box 6.7. Representative student answer to Problem Four Part Three of the PBL thermal physics module.

Once again there is evidence that students were using their modelling skills from the answer shown above in Box 6.7. Students, once again, had to make valid assumptions in order to successfully solve the Problem. It can also be seen from these students' answer that they have considered three stages of heat removal required to freeze the fish and maintain them frozen on the journey home. The students are reinforcing and further developing their knowledge of latent heat, thermal transmittance and specific heat capacity in carrying out the calculations involved in this part of the Problem. The mistake made by these students, not calculating CP at the new temperatures was very common, with only one group avoiding it. This is cause for concern as it displays the fact that students don't understand the concept of engine efficiency. Although seven out of the ten groups managed to answer Part Two of the Problem correctly, they have obviously not gained a complete understanding of the concepts involved. To avoid this happening again it will be necessary to revise the Problem, either rewriting it in smaller steps or changing it completely.

6.3. Assessment of students' understanding of thermal equilibrium and heat transfer

6.3.1. Problem Four pre test

As this Problem builds on students' previous knowledge of thermal equilibrium and heat transfer we decided that we would pre and post test these concepts to assess the effect of the Problem on students' understanding of them. There has been no previous research into students understanding of these particular topics, and thus no results to compare with, so we developed our own pre and post tests for this Problem.

The pre test, presented below in Box 6.8, assesses students understanding that the amount of heat required to raise or lower the temperature of a substance is proportional to the difference between its temperature and the required one and specific heat capacity (equation 1 Box 6.6), as well as their knowledge of thermal equilibrium. In order to draw an appropriate graph, (see Box 6.9 below) students must realise:

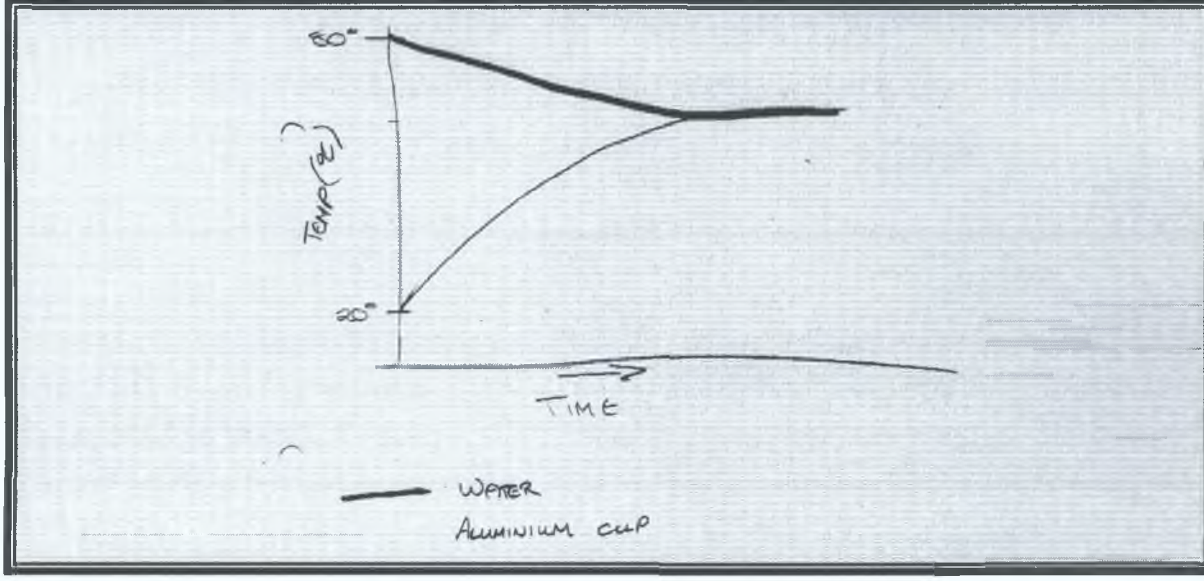
- The water and the metal will eventually come to thermal equilibrium with each other

- The temperature that this equilibrium will be at is dependent on the mass, temperature difference and specific heat capacity
- As the first two factors are the same for both the metal and the water, the only thing to be considered is the specific heat capacity
- Assuming no heat loss to the surroundings, the water and metal will reach equilibrium, nearer to the temperature of the water (the higher), as it has a higher specific heat capacity

Pre Test:

An amount of water at 80°C is poured into an aluminium cup of equal mass, which is at 20°C. Sketch temperature of water versus time and temperature of aluminium versus time on the one graph.

Box 6.8. *Pre test given to students before Problem Four of the PBL thermal physics module.*

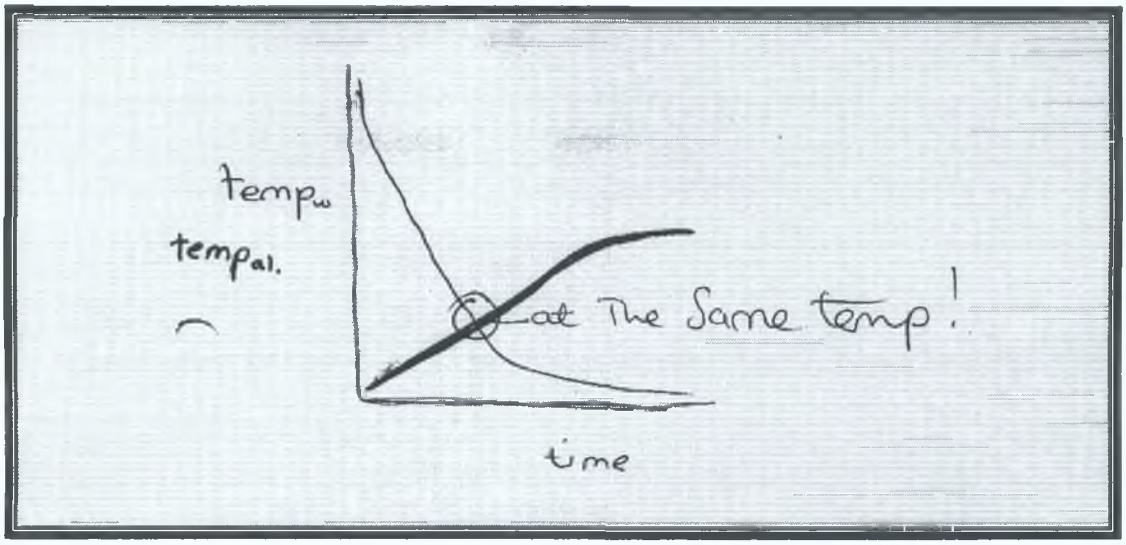


Box 6.9. *Representative correct answer to the pre test given before Problem Four of the PBL thermal physics module.*

6.3.2. Pre test results

Almost half the students correctly answered the pre test (see table 6.1). The responses of those students who answered it incorrectly fell under two categories; those that indicated an incorrect equilibrium temperature and those who drew incorrectly shaped curves. The most common incorrect response was that of indicating a lower equilibrium temperature than the actual one. This may be a result of students indicating that the system would eventually reach room temperature. The difficulty in determining if this is the case lies in the fact that students didn't indicate time on their axis and so it is not possible to determine if the equilibrium position they are showing is after a long or short amount of time has passed. Those students that indicated a middle equilibrium temperature either didn't take specific heat capacity into account, or were not aware that water has a much higher specific heat than aluminium.

In relation to the heating and cooling curves, there were two main incorrect shapes, linear rather than exponential and graphs increasing after equilibrium had been reached (see Box 6.10 below) This is surprising, as students demonstrated an understanding of the Newton's Law of Cooling and thermal equilibrium through their completion of Problem One Part Two (see section 3.2.3.) Consequently, these incorrect curves may show that students did not transfer the knowledge gained from Problem One; they may also indicate that we were too optimistic in our assessment of what students have understood from Problem One. Another possible explanation is that these incorrect curves may be a result of students' inability to represent concepts graphically rather than misconceptions regarding the physical concepts themselves.



Box 6.10. *Representative incorrect answer to the pre test given before Problem Four of the PBL thermal physics module.*

	1st Years	**2nd Years**
Correctly shaped curves for both aluminium and water	31%	62%
Correctly shaped curves on two different graphs	35%	0%
Incorrectly shaped graph: Equilibrium for one instant in time	12%	0%
Incorrectly shaped graph: Linear rather than exponential	4%	23%
Low equilibrium temperature	38%	29%
High equilibrium temperature (Correct)	8%	0%
Middle equilibrium temperature	15%	46%
No indication that they reach an equilibrium temperature	35%	0%
Indication that system will eventually reach room temperature	8%	23%
Mention Q = mcΔT	8%	15%
State that equilibrium position depends on specific heat capacity	4%	31%

Table 6.1. *Results of Pre test on students understanding of thermal equilibrium.*

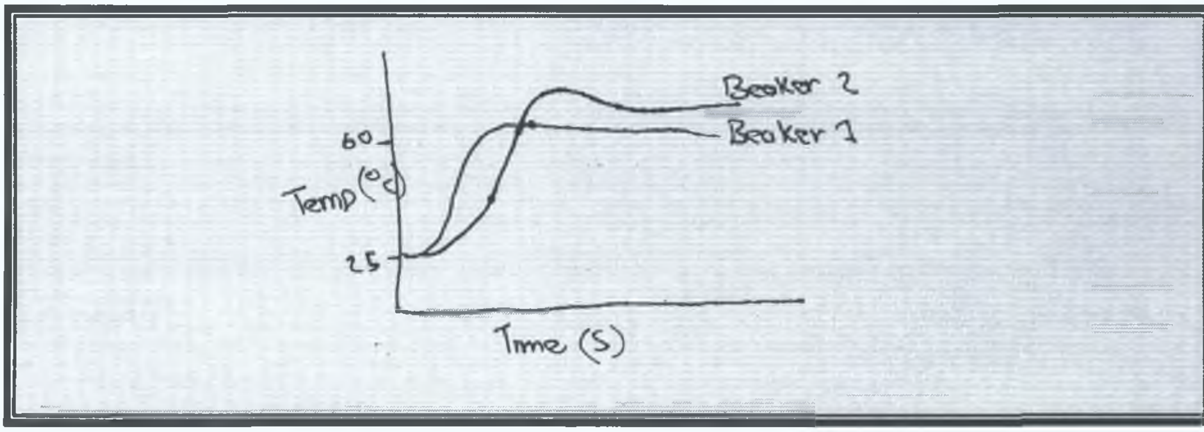
6.3.3. Problem Four post test

The post-test, presented below in Box 6.11, assesses the same concepts as the pre test, however students are provided with more information, they are told the specific heat capacity and thermal conductivity of the substances in question. This means that the post-test has the added objective of assessing if students understand the difference between these two quantities and what they relate to. A representative correct response to the post test is shown below in Box 6.12.

Post Test:

A small piece of copper at 75^{0}C is placed into an insulated beaker of water at 25^{0}C. A piece of aluminium (which has a higher specific heat capacity but a lower thermal conductivity) of the same mass and also at 75^{0}C is placed into an identical insulated beaker. Will the final temperature of the water in the second beaker be greater, smaller or the same as that of the water in the first? Sketch temperature of the water versus time for both cases on the one graph.

***Box 6.11.** Post test given to students after they had completed Problem Four of the PBL thermal physics module.*



***Box 6.12**. Representative correct answer to post test given to students before Problem Four of the PBL thermal physics module.*

6.3.4. Findings of the post test

Approximately one third of Science Education and Physics students drew correctly shaped curves in answering the post test. This was an increase in the number of correct responses from the Physics students when compared to the pre test, but a decrease for the Science Education students. One of the reasons for this may be due to the additional information that was given in the question. It is clear from the variety of answers regarding the temperature of water in the beakers (see table 6.2) that students were not sure if the thermal conductivity or the specific heat capacity of the metals were relevant. Only 21% of first years and none of the second years correctly answered that the water would be higher in the second beaker due to the higher thermal conductivity of the aluminium.

The trends regarding the equilibrium temperatures that were visible in the pre tests were also apparent in students' answers to the post tests. There was a drop in the number of students who indicated a middle temperature between the two starting ones, this may have been a result of the fact that the specific heat capacities of the metals were given, which may have reminded students of their relevance.

Students' problems with recognising the relevance of specific heat and thermal conductivity and understanding the difference between them are apparent in their written answers to the post tests. However, Problem Four does not address this issue explicitly. Students are required to use the concept of specific heat capacity as well as thermal conductivity in Part Three (See section 6.2.5), although students should develop an understanding for these concepts the Problem does not directly require them to differentiate between them. The fact that the post test gives students both the specific heat capacities and the thermal conductivities (which are irrelevant) may cause them to think that they are both significant and this may explain the volume of incorrect responses.

	1st Years	2nd Years
Correctly shaped curves for water in both beakers	39%	36%
Correctly shaped curves on two different graphs	11%	0%
Correctly shaped curves of metals rather than water	11%	7%
Low equilibrium temperatures	29%	0%
High equilibrium temperatures	14%	43%
Middle equilibrium temperatures	25%	14%
Indication that system will eventually reach room temperature	14%	50%
Mention $Q = mc\Delta T$	29%	14%
Final temperature equal in both beakers (both reach room temperature)	7%	29%
Final temperature equal in both beakers (specific heat and thermal conductivity cancel each other out)	11%	14%
Final temperature higher in beaker with aluminium, no explanation	14%	14%
Final temperature higher in beaker with aluminium due to higher specific heat (Correct)	21%	0%
Final temperature higher in beaker with copper due to higher thermal conductivity	4%	7%
Final temperature the same but it takes aluminium longer to reach it due to lower thermal conductivity	18%	43%
Final temperature the same but it takes aluminium longer to reach it due to higher specific heat capacity	0%	43%

Table 6.2. *Result of post test on students understanding of thermal equilibrium.*

6.3.5. Comparison of Science Education and Physics students' responses

It was interesting to note that in the pre test 31% of Science Education students stated that the equilibrium position would depend on the specific heat capacity of the substance in question, however, none of them correctly answered that the water in the beaker with the aluminium would be higher due to its higher specific heat capacity in the post test. We feel that this is because although students knew that there was some dependence, they were unsure what the exact relationship was and so when given all the information in the post-test became confused. In contrast to this, 4% of the Physics students mentioned that the equilibrium temperature was dependent on the specific heat capacity in the pre-test, however 21% of them correctly answered that that the water in the beaker with the aluminium would be higher due to its higher specific heat capacity in the post test. None of the Science Educations students took a mathematical approach to solving the problem, whereas 14% of the physics students opted for that type of method. As well as this, twice as many Physics students mentioned equations in their answers.

6.3.6. Conclusions from the pre and post test results

Although the number of correct answers didn't improve after students had completed the Problem, we think that this is due to the fact that it didn't require students to use their graphing skills. Although students' understanding of the physics could have improved, it wouldn't necessarily result in an improvement in their graphing ability. This was also evident in Question One on the final exam paper, were students were asked to draw heating and cooling curves (See section 3.3.2), although students drew incorrectly shaped curves, they then correctly explained the physics. As students were not required to give an explanation of their reasoning in either the pre or post test, it is not possible to determine how much of the incorrect answers were as a result of difficulties with graphing.

6.3.7. Recommendations for development of the pre and post tests

The pre and post tests that we developed for Problem Four were suitable to determine students understanding of thermal equilibrium and specific heat capacity, however as they were graphically based and the Problem wasn't, it is difficult to draw conclusions on the effect of the Problem on students development. Although students may have gained an understanding of the concepts from completing the problem, their difficulties with drawing graphs, may have lead to them not being able to express this understanding and so to improve the reliability of the findings it will be necessary to change the format of the pre and post tests so that it matches the format of the problem. An alternative would be to keep the same format but also ask students to provide a written explanation of their reasoning.

This would provide a more accurate description of the effect of the Problem on students understanding as well as having the added advantage of demonstrating the amount of students having difficulty representing information graphically.

6.4. Assessment of students' understanding of thermal equilibrium and latent heat

6.4.1. Introduction

Question Three on the final exam paper was designed to assess students understanding of latent heat and thermal equilibrium, and so provides an indication of the effect that Problem Four had on students' understanding of these concepts. The question consists of two parts and is presented below in Box 6.13.

Question 3

Part 1

On a warm summer's day you're going on a long walk, and you decide to bring a thermos flask with cold water. You fill the flask with 500 g of water at +20 °C and 50 g of ice at –20 °C, and screw on the top.

a) How much heat is needed to raise the temperature of the ice to -10 °C?

b) Show that all of the ice is likely to melt. State which assumptions you make.

c) Calculate the final temperature if you leave the ice-water mixture alone for a long time.

Part 2

The metal gallium has a melting temperature of 29 °C. You have a small amount of gallium at temperature of 50 °C, which is cooling down in a 20 °C lab.

d) Sketch the temperature of the gallium as a function of time. Explain briefly.

e) Sketch the heat flow out of the gallium as a function of time. Explain briefly.

Box 6.13. *Question Three of the PBL thermal physics module final exam.*

6.4.2. Comments on parts a, b and c

The first part of these questions was designed to encourage students to think about the concepts that were necessary to solve the next two parts. It was a straightforward calculation, involving the use of the specific heat capacity formula, which students had seen many times during the module. It didn't cause any difficulties; all students correctly identified the relevant concept and formula with 86% of students calculating the correct answer. The remaining students didn't obtain the correct answer due to simple numerical errors, such as not converting the mass to kilograms.

Part b of the questions assessed students understanding of thermal equilibrium. In order to answer the question they needed to realise that the heat would flow from the water into the ice until thermal equilibrium was reached; 82 % of students stated this in their response to the question. Students also needed to recognise that as there was ten times more water than ice and as it had twice the specific heat capacity of ice there was enough energy available to melt the ice. One of the difficulties for students in answering this question was that they thought that some form of calculation was required, when an explanation would suffice. However, even those students that attempted a calculation explained their reasoning and there was evidence that they understood the concept. 34% of students gave a full, correct explanation and another 30% provided incomplete correct explanations.

Part c of the questions required students to calculate the temperature of the ice water mixture when it had come to thermal equilibrium. This was the part of the exam that required the most mathematical skills. Once students had an understanding of the physical concepts involved, they had to relate and manipulate equations in order to calculate the required temperature. 55% of students recognised that the heat would flow from the water to the ice and that they could use $Q = mc\Delta T$ to calculate the relevant heat. However students had some difficulties with determining expressions for the heat flow into the ice, with only 11% correctly expressing this. This question is similar to Part Three of Problem Four, where students have to determine the amount of heat necessary to be removed to freeze the fish and maintain them frozen. The difficulties that students had in taking into account all of the relevant heat (see section 6.2.5.) were also evident in their answers to the exam question. Most students realised that the heat into the ice would involve that needed to bring it to zero degrees Celsius and to melt it, however neglected to take into account the heat transferred to the ice from the water once it was melted. Although most students did not calculate the correct equilibrium temperature, it was evident from their answers that they understood the physics involved, but had difficulties in applying it mathematically.

6.4.3. Comments on parts d and e

Parts d and e were similar to the pre and post tests in that students were required to draw heating and cooling curves. Consequently the exam question and pre and post tests had some learning objectives in common. All questions assessed students understanding of thermal equilibrium and ability to draw appropriately shaped curves. In comparing students' answers to the pre and post test with those to the exam question, it can be seen that their ability to draw heating and cooling curves has remained static. This may be explained by the fact that students were not required to draw graphs in any of the Problems after Problem Four coupled with the fact that they received little feedback from the pre and post test answers (see section 3.3.2)

The exam question also assessed students understanding of latent heat. 66% of students demonstrated an understanding of latent heat by drawing a constant temperature during the phase change. Only 18% of students indicated that heat flow was constant during the phase change, 42% of students showed heat flow as continuing exponentially, even during the phase change. As these students had shown an understanding that temperature is constant during a phase change, their graphs may demonstrate a misunderstanding about the relationship between heat flow and temperature.

6.5. Conclusion

One of the main outcomes of Problem Four was developing students modelling skills further. Each part of the Problem required students to make valid assumptions and simplifications. As the modelling aspect of each part of the Problem built upon the previous but was slightly different it enabled students to adapt the models that they had first developed. In this way students gained an insight into the effectiveness of this method of solving problems. This aspect to the Problem also helped students realise that the modelling that they were completing was not just "guesswork" but was actually a valid method of assessing situations using physical concepts.

Another aspect of Problem Four was that it encouraged students to transfer their previous knowledge from the module. Part One of the Problem draws on the physics that students have learned from Problem One, involving heat transfer and thermal transmittance.

Students' reports on Problem Four show that they have completed research into the relevant concepts, they give plenty of references. In addition to this, more students numbered equations and explained their thinking in their reports.

There is evidence from students' answers to Question Three of the final exam that they have an understanding of latent heat and thermal equilibrium. Students also demonstrate the ability to calculate the heat required to raise the temperature of a substance by a certain amount.

Chapter Seven Discussion of Problem Five

7.1. Introduction to Problem Five

There were five Problems developed and implemented for the first delivery of the thermal physics module through PBL. The first four of these Problems were implemented again during the second delivery of the module. Any changes we made to these Problems as well the outcomes of implementing them have been discussed in Chapters Three to Six. The fifth Problem, which was designed to introduce students to some of the microscopic concepts involved in thermal physics, didn't achieve the desired learning outcomes. Consequently, we decided to develop a new question involving these concepts. This chapter outlines the development and implementation of the new Problem Five.

7.2. Development of Problem Five

7.2.1. The learning outcomes of Problem Five

Before developing a Problem it is necessary to establish what the learning outcomes will be in order to ensure that it meets the requirements. We decided that the main concepts that we wanted students to develop an understanding of were the assumptions of the kinetic theory, the relationship between kinetic energy and temperature and interatomic collisions. These were similar to the learning outcomes of the old Problem; however that also involved diffusion. The learning outcomes of the new Problem were:

When students have completed the problem they will have an understanding of:

- The assumptions of the kinetic theory model of an ideal gas and why they are necessary.
- The relationship between temperature and kinetic energy.
- The root mean square speed equation and how to apply it.

- The mean free path equation and how to apply it.
- The microscopic effects of an increase in temperature on a gas at constant volume.
- How the kinetic theory of an ideal gas may be applied to a real life situation.
- The fact that the theory is only a model and therefore is not an exact explanation of the molecular behaviour of a gas.

Once we had establish a list of the desired learning outcomes we needed to find a suitable topic to base the Problem around that would enable the students to achieve these objectives. This proved to be very difficult, as it had to be something relevant and "real world" as well as allowing the exploration of microscopic topics. On researching the kinetic theory of gases in an undergraduate textbook[1] one of the facilitators came across a question on a dark nebula, which assessed students' ability to apply the equations derived from the kinetic theory. We decided that an astronomy topic, such as used in this question would be ideal for the Problem. Firstly it would be something that the students could relate to, particularly relevant for those studying Physics and Astronomy and secondly, it would allow the relevant concepts to be explored.

7.2.2. Research into the concepts involved in Problem Five

The first step we took in writing the new Problem was to solve the question from the undergraduate Physics textbook. Although this question was a "challenge problem" and required some thought, it could mostly be solved through substitution into equations, which isn't what we wanted. We decided to adapt one or two parts of this question to form the basis of our Problem. In order to do this it was necessary to research into dark nebula, as our students would not be given any information and so it was necessary to see if they could complete this research.

When research into dark nebulae was begun, it was soon discovered that they would not be a suitable topic to form the basis of an exploration into kinetic theory. The reason for this was their structure. It was discovered that dark nebulae are quite dense and that they are formed from dust and molecular rather than atomic particles [2,3,4]. As a result of this the gas in the nebulae cannot be treated as ideal and so the kinetic theory won't hold.

While researching dark nebulae, other interstellar phenomena were discovered and one of them, hydrogen clouds, seemed to fit the description needed. We discovered that there were a number of different types of region in the interstellar medium[5]; those that contain neutral hydrogen (HI regions) were those of interest to us. We decided that structuring the Problem around a hydrogen cloud in a HI region of space would be successful, as these clouds are made up of neutral atomic hydrogen, are not very dense[6] and so can be examined using the kinetic theory of gases. The Problem is presented below in Box 7.1.

Thermal Physics – Problem Five

Part One

You are an astronomer studying the Interstellar Medium (ISM). You know that the ISM is gas, that it is mostly made of hydrogen and that it tends to clump in clouds. You have observed a hydrogen cloud in a HI region of space. You want to calculate the pressure inside the cloud in order to determine if it is likely to collapse and form a star. List any assumptions that you need to make about the particles of the cloud and calculate the pressure.

Part Two

Mapping of the cloud using a radio telescope shows emission corresponding to a wavelength of 21.11cm. This indicates to you that the cloud is composed of atomic hydrogen. However, you are wondering if atomic collisions may lead to the formation of molecular hydrogen in the cloud. Carry out calculations to see if this is likely.

Part Three

You have discovered another cloud; the only difference is that it is 10K colder. What effect will this have on the pressure, density and likeliness of forming molecular hydrogen?

Box 7.1. Problem Five of the PBL thermal physics module.

7.3. Students' response to Problem Five

7.3.1. Comments on Part One

The Problem had to start off by introducing the students to the kinetic theory of gases, as this was a prerequisite to them forming an understanding of the concepts and equations that were involved in the rest of the Problem. We decided that what the students needed to examine first were the assumptions of the kinetic theory. It was difficult to develop a question that was open ended and required students to research into this topic. The main problem was that as students had no experiences of microscopic concepts, thinking about the question from this point of view was not something that we expected them to do intuitively. This is unlike the other Problems, where most students had some experience of the concepts involved, or could see their relevance. For example, with part one of Problem One (see section 3.2.1.) students would instinctively know some factors affecting the rate of the temperature drop, or with part one of Problem Four, students would instinctively think about the ice melting due to heat flow into the cool box. As a result we decided that the first part of the Problem should deal with a macroscopic concept that the students were familiar with and then be guided towards thinking about the microscopic concepts.

Students are asked to determine the pressure inside a gas cloud, we explain that it is to determine if the cloud is going to collapse in order to give students a viable reason for wanting to carry out the calculation. The concepts needed to solve this problem are familiar to students, they have seen the Ideal Gas Law in Problem One and Three and we felt that this would be the first concept that the students thought about. Thus, this provided a starting point. However, we still needed to guide the students towards thinking about the Problem microscopically, to do this we asked them to list the assumptions that they needed to make about the gas particles in order to calculate the pressure inside the cloud.

As students intuitively think about the Ideal Gas Law, the next step is to question its applicability. Students know from previous Problems that in order for the Ideal Gas Law to be applicable the gas must be at high temperature and low pressure. Students then need to think about what this means in terms of the gas particles.

One difficulty that we had with this part of the Problem was the fact that some students did not list their assumptions or else approached the Problem by trying to calculate whether the star would collapse (see section 7.2.2). In order to address these problems, the question was reformulated (shown below in Box 7.2), firstly to stress the necessity of stating the assumptions about the particles, and secondly to de-emphasise the collapsing of the cloud.

> ***Part 1***
>
> *You are an astronomer studying the Interstellar Medium (ISM). You know that the ISM is gas, that it is mostly made of hydrogen and that it tends to clump in clouds. You have observed a hydrogen cloud in a HI region of space. You want to calculate the pressure inside the cloud and think about using the Ideal Gas Law. What assumptions do you need to make about the particles of the gas in order to do this? Do you think this is a valid method of calculating the pressure?*

Box 7.2. *Reformulated Part One of Problem Five of the PBL thermal physics module.*

7.3.2. Students' answers to Part One

Our hypothesis that students would first consider the Ideal Gas Law as a method of calculating the pressure was correct. The students soon noted that because the gas is at a high temperature and low pressure, (not near condensing) that it could be treated as an ideal gas with little effect on calculations. However, students had difficulty relating this to the properties of the gas particles.

One of the reasons that students found this question difficult was that they are not used to thinking microscopically. If students were having difficulties in determining the assumptions that were required, facilitators would question them in order to guide them towards a solution. For example, many students said that they were assuming that the gas was not near condensing, as they were applying the Ideal Gas Law. Facilitators would then ask students what that meant in relation to the gas particles. Students usually replied that it meant there were no interactions between them, which is one of the assumptions of the kinetic theory. In this way students began to relate their macroscopic assumptions to the gas particles and, through this, to develop their own understanding of the assumptions of the kinetic theory of gases.

Eventually, eight out of the ten groups calculated the pressure using the Ideal Gas Law, and four of these correctly listed some of the assumptions of the kinetic theory of gases. A representative answer is shown below in Box 7.3. The other four groups either listed the approximations they were making about the macroscopic properties of the cloud, such as assuming its volume, or else ignored this part of the question completely.

(1)

- The cloud consists of large numbers of tiny particles that are far apart relative to their size. i.e. the cloud has a low density. We are taking the density of our hydrogen cloud to be 5 atoms/cm^3 or 5*10^{6}atoms/m^3. (http://www.daviddarling.info/encyclopedia/H/HI.html) This means that the particles are so far apart we can assume there will be no interactions between them.

(2)

- The gas particles undergo elastic collision only. This means that there is no energy loss between particles when they collide but there is an equal energy transfer from one particle to the next.

(3)

- The gas particles are in constant rapid motion due to having an equal amount of kinetic energy. The kinetic energy of the particle is directly related to the velocity of the particles as:

$$KE = \tfrac{1}{2} mv^2 \qquad \textit{EQN 5}$$

KE = kinetic energy of particle

m = mass of particle

v = velocity of particle

(4)

- There are no forces of attraction or repulsion between the gas particles.

(5)

- The average kinetic energy of the particles depends on the temperature.

  As kinetic energy is proportional to velocity, the higher the temperature means the higher the velocity

As we are assuming that the particles in the hydrogen cloud follow this kinetic theory of gas particles i.e. behave as an ideal gas, we can use the ideal gas law (eqn 4: PV=nRT) to calculate the pressure of a typical hydrogen cloud in a HI region.

***Box** 7.3. Representative section of a student answer to Problem Five Part One.*

It is clear from the last paragraph of these students' answer that they are aware that assuming the gas is ideal means the particles fulfil the kinetic theory assumptions. They also show an understanding of the link between the macroscopic properties of the cloud, in the first paragraph of their answer. They explain the relationship between kinetic energy of the gas particles and temperature in paragraph five. Overall it is evident from these students' answer that they have developed their own understanding of the assumptions of the kinetic theory of gases.

The three groups who thought that they were required to determine if the cloud was likely to collapse, carried out a calculation but didn't really think about the physics behind what they were doing. A typical answer given by these groups is shown below in Box 7.4.

Assumptions made: what assumptions are you making about the particles of the cloud?

The assumptions made in this part are as follows: ref?

- The radius of the cloud is 5×10^{17} m
- The mass of the hydrogen atoms 1.67×10^{-17} units?
- The temperature in the cloud 100K

ref?

Equations and laws used:

It can be said that the kinetic energy of a gas molecule can be seen by the following:

$$1/2mv^2 = \overset{3/2}{\cancel{k}}T$$

$$\Rightarrow v^2 = \frac{2kT}{m}$$

← where does this come from? and why can you use it?

The cloud will collapse if: $$\frac{2GM}{r} > \frac{2kT}{m}$$

↳ where does that come from?

Therefore in order to find the mass of this collapsing cloud it can be said:

$$M > \frac{kTr}{m_{h_2} G}$$

Subbing in the values:

$$M = \frac{(1.38 \times 10^{-23})(100)(5 \times 10^{17})}{(2 \times 1.67 \times 10^{-27})(6.6 \times 10^{-11})}$$

$$M = 3.13 \times 10^{33} kg$$

$$M = 1573 M_{\odot}$$

Now that the maximum mass of the cloud is found the pressure can be determined by:

$$P = \frac{F}{A} \tag{2}$$

$$P = \frac{\frac{GMm}{r^2}}{4\pi r^2}$$

$$P = \frac{\frac{(6.6 \times 10^{-11})(3.13 \times 10^{33})(1.99 \times 10^{30})}{(5 \times 10^{17})^2}}{(4\pi)(5 \times 10^{17})^2}$$

$$P = 5.23 \times 10^{-19} Pa$$

too many s.f.

The pressure is expected to be low as the gravity must be higher than that of the pressure, causing the collapse. than that of p?

Box 7.4. Representative incorrect student answer to Problem Five Part One.

Although these students do give the estimations that they are making about the macroscopic properties of the cloud in paragraph one of their answer, they fail to mention the microscopic properties at all, even though the question stated explicitly that they should do so. Their method of calculating if the cloud will collapse is valid, however they don't explain were the equations come from or why they are applicable. It is evident that these students misinterpretation of the question resulted in them failing to achieve the learning objectives. However, now that the question has been reformulated, as shown above in Box 7.2, this should not happen again.

In assessing the students' answers to this part of the Problem, as with Part Three of Problem Two (see section 4.2.5) we rewarded those students who had justified and explained their method. Those students who explained the assumptions they were making about the gas particles and justified the use of the Ideal Gas Law received full marks. Those who determined if the star was going to collapse and explained and justified their method could achieve a possible 70% and those who didn't a possible 50%.

7.3.3 Comments on Part Two

We decided that Part Two of the Problem should introduce students to the root mean square speed and mean free time equations. In order to do this we asked them if it was likely that atomic collisions would lead to the formation of molecular hydrogen in the cloud. We guided the students towards thinking about interatomic collisions, as we wanted them to consider the mean free time equation in order to estimate the time between collisions in the cloud. In deriving this equation we had to think about the distance that particles could travel before meeting another (see box 7.5 below) as well as the effect of the speed of the particles (see Box 7.6 below). We intended that through this, students would develop an understanding of the theory behind the equations as well as of the relationship between kinetic energy and temperature.

The mean free path equation (1) can be used to calculate the average distance travelled by particles between collisions.

$$\lambda = \frac{V}{4\pi\sqrt{2}r^2 N} \qquad (1)$$

Where: V = volume r = particle radius

N = no. of particles

This equation takes the size and number of particles into account. Thus the bigger the particles and the more of them per unit volume the less distance there will be between collisions. It can also be written using the macroscopic properties of the gas:

The Ideal Gas Law

$$pV = NkT \qquad (2)$$

Where: p = pressure k = Boltzmann's constant T = temperature

So

$$\frac{V}{N} = \frac{kT}{p} \qquad (3)$$

Subbing equation 3 into equation 1

$$\lambda = \frac{kT}{4\pi\sqrt{2}r^2 p} \qquad (4)$$

If the temperature is increases at constant pressure the mean free path increases, which is expected as the gas expands and the distance between particles increases. If the pressure is increased at constant temperature, the gas contracts and so the mean free path decreases.

Box 7.5. *The mean free path equation, which is used to calculate the average distance travelled by particles between collisions.*

In order to calculate the average time between collisions it is necessary to divide the mean free path by the speed of the molecules, which can be derived from the relationship between the kinetic energy of the particles and the temperature:

$$\frac{1}{2}m(v^2)_{av} = \frac{3}{2}kT \qquad (5)$$

Where: m = particle mass v = particle speed

$$\left(v^2\right)_{av} = \frac{\left(\frac{3}{2}\right)kT}{\left(\frac{1}{2}\right)m} = \frac{3kT}{m} \qquad (6)$$

Subbing 6 into 5:

$$v_{rms} = \sqrt{\left(v^2\right)_{av}} = \sqrt{\frac{3kT}{m}} \qquad (7)$$

Alternatively, students may have used the mean free time equation (shown below), which is the mean free path divided by the molecular speed. This still involves calculating the speed and taking into account the size of the particles and volume of the gas and so students still fulfil all the requirements if they use it.

$$t_{mean} = \frac{V}{4\pi\sqrt{2}r^2vN} \qquad (8)$$

Box 7.6. *The root mean square speed equation, used to calculate particle speeds.*

Although we thought that this part of the problem would result in students developing an understanding of the mean free path and root mean square speed equations, it turned out that it could be solved through substituting figures (see section 7.2.4). This was the same difficulty that became evident with Part Two of Problem One after it was first delivered (see section 3.2.2) While it was more challenging than a typical end of chapter question as students were given little information and had to complete research to estimate values and obtain the right equations, it still wasn't a successful PBL problem. In order to ensure that this part of Problem Five is successful in developing students' understanding of the molecular properties of ideal gas particles it was reformulated as shown below in Box 7.7.

> ***Part 2***
>
> *Mapping of the cloud using a radio telescope shows emission corresponding to a wavelength of 21.11cm. This indicates to you that the cloud is composed of atomic hydrogen. However, you are wondering if formation of molecular hydrogen in the cloud is likely. Carry out calculations to determine if this is probable. Explain the relevance and origin of any equations that you use.*

Box 7.7. *Reformulated Part Two Problem Five of the PBL thermal physics module.*

Removing the line indicating that molecular collisions take place means that the students won't automatically look this up and so will make the mean free time equation a less obvious choice, ensuring students have to research into the concepts before discovering the equation. As students will be less certain that atomic collisions are what they need to focus on, they will be required to think about the equations in more detail to ensure that they are relevant to the Problem. Stating clearly that students must justify the equations they use should ensure that students explain their reasoning clearly and consequently gain a full understanding of the physics behind the equations.

It may be objected that Problem Five is not a kinetic problem, but an equilibrium problem, since the collision time is likely to be much shorter than the lifetime of the Hydrogen cloud; the validity of the classical approximation of the collision cross section by πr^2 could also be debated. Equilibrium problems form an important part of thermal physics, and groups could investigate the Hydrogen cloud in a more sophisticated way, for example, by stating that for a 100 K cloud in equilibrium much of the Hydrogen is in fact likely to be molecular because the binding energy is 4.5 eV (which would correspond to a Boltzmann temperature of about 50 K). We did not encourage this, as it did not meet the aims of the Problem.

7.3.4. Students' answers to Part Two

All groups carried out the calculations of this part of the Problem correctly. Every group succeeded in obtaining a value for the number of collisions per unit time and from this an estimation of whether molecular hydrogen was likely to form. However, eight out of the ten groups didn't explicitly show an understanding of the physics behind the equations they used to solve the Problem. A representative answer to this part of the Problem is shown below in Box 7.8.

In this part of the problem we are told that the cloud shows emission corresponding to a wavelength of 21.11cm, this tells us that the cloud is composed of atomic hydrogen. We are asked to determine if the formation of molecular hydrogen is likely. Firstly we set about determining the distance a hydrogen atom would have to travel in our cloud to collide with another hydrogen atom in a random perfectly elastic collision. This distance is called the mean free path and was determined using equation 2.1. Where N is the number of atoms in the cloud, V is the volume of the cloud and r is the radius of a hydrogen atom

$$\lambda = \frac{KT \quad (KT)}{4\sqrt{2}\pi \; r^2 P_{(p)}} \quad \checkmark \qquad \textit{Equation2.1}$$

The number of atoms and the volume of the cloud had already been determined in part 1. We determined the mean free path to be 4.5×10^{13} m. Next we set about determining the velocity at which these atoms were moving using equation 2.2 where R is the gas constant which is experimentally determined to be the same for all gases, T is the temperature of the cloud and M is the molar mass of hydrogen determined to be 2g/mol and referenced from Giancoli.

atomic H → 1 g/mol
H_2 → 2 g/mol

$$V_{rms} = \sqrt{\frac{3RT}{M}} \quad \checkmark \qquad \textit{Equation2.2}$$

The root mean squared velocity of the atoms was determined to be 1248.6m/s. This is the average velocity of the atoms. Next we used equation 2.3 to determine the time it would take for a collision to occur

$$t = \frac{d}{v} \qquad \textbf{\textit{Equation2.3}}$$

Using equation 2.3 we found out that a collision would occur every 3,604,036,521 seconds or 114.3 years! As the time between collisions is of huge magnitude it is highly unlikely that molecular hydrogen will be formed in this cloud. The

Box 7.8. Representative student answer to Problem Five Part Two.

It is evident from these students' answer that they have discovered the correct equations and understand what they are calculating. They state that the mean free path equation is used to estimate the average time between particle collisions (lines four to six) and that they are using the root mean square speed equation to calculate the particles speed in order to determine the mean free time. Although these students do not show explicitly that they understand the concepts behind the equations, it is evident that they have carried out research, as they give references (line 14) and are able to apply the equations and so must have developed some understanding of their origin.

There were two groups that did show an understanding of the origin of the Physics behind the equations, representative sections of their answers are shown below in Boxes 7.7 and 7.8.

- As the model of our cloud complies with the kinetic theory of ideal gas particles we know that the volume hydrogen atoms are tiny ($5.2*10^{-31}m^3$)(website) compared to the volume of the cloud ($6.9*10^{51}m^3$). i.e. the particles have a very low density of $5*10^6$ atoms. As the volume of hydrogen atoms are so small in such a large volume of space this would indicate that it is not likely that they would collide.

- From the kinetic theory of gas particles we know the hydrogen atoms are in constant rapid motion due to their kinetic energy. The kinetic energy of a particle is proportional to its temperature. As $KE=1/2mv^2$, an increase in temperature will increase the velocity v of the particle. Our hydrogen cloud is at a temperature of 125K. This temperature is

quite low (-148°C). This means the atoms of hydrogen have not got a large amount of kinetic energy and hence are not moving at high speeds. This would indicate again that it is not very likely the hydrogen atoms will collide as the faster they move would mean more collisions per unit second.

- From part 1 we have found the pressure of our cloud to be $8*10^{-15}$Pa. This pressure is very low. This means that the gas particles are not compressed ? and are spread out further than a gas at a higher pressure. This again would indicate that the particles are not likely to collide with each other.

These points have shown that in a hydrogen cloud, assuming it behaves as an ideal gas, the hydrogen atoms are not likely to collide and form molecular hydrogen. We can now carry out calculations to determine if this indeed is the case.

an atom can travel before [illegible] another

Box 7.7. Representative section of students' answer to Part Two of Problem Five of the PBL thermal physics module.

It is evident from this section of the students' answer in Box 7.7 above that they are thinking about the situation and reasoned what their calculations should show. Before applying the equations we promoted this method of approaching problems throughout the course, for example in Part One of Problems One and Two and these students' answer is evidence that they have gained this skill. After explaining what they thought was going to happen, these students went on to apply the equations and found that their hypotheses were correct. It is evident from their answer that they have developed an understanding of the mean free time equation, along with ability to apply it.

First we need the velocity of the atoms of hydrogen. We do this using this equation;

$$\frac{1}{2}mv^2 = \frac{3}{2}kT \qquad (4)$$

We can use this equation because we know it's a confined volume of gas, at a constant pressure and temperature, that aren't particularly high. or low

$$v = \sqrt{\frac{3kT}{m}}$$

$$mv^2 = 3kT \qquad (5)$$

rearrange before subbing in values

$$(1.67\text{x}10^{-27})v^2 = 3(1.38\text{x}10^{-23})(50)$$

$v = 1113.3\text{m/s}$

λ = mean free path = average distance part

Box 7.8. Representative section of students' answer to Problem Five Part Two of the PBL thermal physics module.

The section of students' answer shown above is evidence that they have gained an understanding that there is a relationship between kinetic energy and temperature. Although these students don't explain the relationship, they use it to derive an expression for the speed of the molecules, which indicates that they must have some understanding of it.

7.3.5. Comments on Part Three

We designed the final part of the Problem to encourage students to think about the validity of assumptions made in different circumstances. Students have to consider the effects of a decrease in temperature on the pressure and density of the cloud. In order to do this, the students must consider if the assumptions that they made in Part One of the Problem are still valid. As the temperature has changed, they need to develop a new model in order to assess the effect of this on the other variables; for example, they could assume a constant volume and apply the Ideal Gas Law.

7.3.6. Students' answers to Part Three

We had hoped that this part of the Problem would encourage students to consider if the model that they developed in Part One was still applicable and to think about the effects of a decrease in temperature on the microscopic properties of the cloud. However, most groups reverted to macroscopic reasoning and applied the Ideal Gas Law. This was appropriate, as the question didn't state that they should reason microscopically, yet students didn't show that they considered if the Ideal Gas Law was applicable or think about the assumptions that they were making.

To ensure that students think about the assumptions that they are making and justify their models the question was reformulated as shown below in Box 7.9. These changes result in the question looking less like Parts One and Two, this should encourage students to see it as requiring serious thought and time, rather than a revision of what they have already answered. Explicitly asking students what effect the decrease in temperature will have on the microscopic properties of the gas particles will ensure that they think about this, as well as encouraging them to understand how they are related to the macroscopic properties of the cloud.

Part 3

You have discovered another cloud; the only difference is that it is 10K colder. What effect will this have on the gas particles and on the pressure, density and likeliness of forming molecular hydrogen?

Box 7.9. *Reformulated Part Three of Problem Five of the PBL thermal physics module.*

About half of the groups gave some reasoning for answering this part of the Problem the way in which they did. One group, whose answer is shown below in Box 7.10, did state their assumptions and justify their method.

3.1 Problem Part 3 - New 10K HI cloud

"What affect will this [the new temperature] have on the pressure, density and likeliness of forming molecular Hydrogen?," - Problem Part 3 text. Using the ideal gas equation (equation 1 in Part 1). We see that temperature is directly proportional to pressure and volume. $T \propto pV$. Now assuming that the number of moles remains constant we can say that if the temperature of this cloud is lower than the cloud in Part 1 the product pV for the new cloud will be proportionally lower. If we also assume that volume is constant (as we are only given that pressure and density are variables) we must say that the lower temperature cloud will have less pressure. With volume and number of moles remaining constant there will be no effect on density. We carried out similar calculations to those in Part 1 and pressure for the new 10K cloud is $1.1\text{x}10^{-16}$ Pa roughly 10 times smaller than the pressure in the original cloud.

The likelihood of collisions between the atoms will decrease with the lower temperature as the time between collisions is inversely proportional to velocity and velocity directly proportional to temperature. $t \propto 1/T$ However the mean free path is directly proportional to pressure and time between collisions therefore $t \propto p/T$.

Box 7.10. Representative student answer to Part Three of Problem Five of the PBL thermal physics module.

These students explicitly state their assumptions, in line four they assume that the number of moles remains constant in order to assess the effect of a drop in temperature on the pressure of the gas and again in line eight they state that they are assuming the volume and number of moles is constant. Their reasoning about the effect of the drop in temperature on the likeliness of forming molecular Hydrogen demonstrates that they have an understanding of the relationships between the mean free path and atomic speeds and temperature. It is evident from this answer that the question has ensured students think about their assumptions and the relationship between the microscopic and macroscopic properties of the cloud.

7.4. Conclusion

The research that the students carried out in solving the Problem was similar to that which we completed in developing it. Students found that Hydrogen clouds in HI regions of the interstellar medium were suitable for the application of the Ideal Gas Law, which helped them appreciate the "real world" aspect of the Problem. The macroscopic properties of these clouds vary widely and there was a range visible in students' answers, however all were reasonable and students gave appropriate references, which is evidence that students have gained research skills through completing the module. In addition to this, there is also evidence that students have gained other skills, for example, they are thinking about the physics of a situation before applying formulae

All groups successfully solved the Problem. It is evident from students' reports that they have gained some understanding of the microscopic properties of an ideal gas, although explicit explanations were missing from some groups' reports.

One of the difficulties with the Problem was that it wasn't open ended enough. The reason for this was because we felt that as the topics were so abstract students needed a little more guidance and so we wrote the Problem with this in mind. This resulted in some students solving Part Two without gaining an understanding of the concepts and Part Three without justifying their methods. However, the question has now been reformulated based on what we have learned from implementing it for the first time. Part One still introduces the students to the microscopic properties using a macroscopic property and a Law that they are familiar with, which should provide enough guidance from what we have seen. The adjustment of Parts Two and Three have also helped to make the Problem more open ended and this should be reflected in students answers the next time the Problem is given.

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Chapter Eight Discussion of Problem Six

8.1. Introduction to Problem Six

We decided that we would like to develop an experimentally based Problem for the PBL module in order to improve students understanding of experimental design and analysis. Consequently, the final Problem of the module, Problem Six, was based on a simple question that we wanted students to answer through the development of their own experimental method. In developing the practical Problem we wanted to:

- Observe the impact of PBL used in a practical context
- Develop students' experimental skills
- Introduce the students to experimental design
- Develop students' graphing and curve fitting skills

This chapter outlines the design of the experiment and the development of the Problem. It also describes how the Problem was implemented and the students' response to it.

8.2. Development of Problem Six

8.2.1. The learning outcomes of Problem Six

The topic chosen for the Problem needed to be suitable for the development of a simple experimental component, as well as something that we could relate to the real world. We first looked at the learning outcomes of all the other Problems to determine if there was another topic, which we felt that should have been included. One aspect that we thought would be beneficial to add was that of radiation. Although heat transfer was covered, specifically in Problems One, Two and Four and in the other Problems indirectly, students had not looked at radiation in detail. It was also beneficial that the topic be related to what the students had studied previously, as the experimental component would be challenging and so having some previous knowledge of the physics would be an advantage. Consequently, we chose the topic of radiation for the experimental Problem.

We then developed a list of learning outcomes that we wanted students to achieve through completing the Problem, these were:

When students have completed Problem Six they will be able to:

- Design and carry out an experiment on the topic of heat transfer by radiation
- Graph data that they have experimentally collected and successfully analyse it
- Develop a mathematical model to describe their data
- Effectively use spreadsheets

When students have completed Problem Six they will have an understanding of:

- Heat transfer by radiation
- The importance of experimental design in ensuring consistency and accuracy

In addition to these knowledge and skills based objectives, the Problem was also designed to achieve the overall objectives of the module, such as improving students research, group work and modelling skills and enabling them to apply their previous knowledge to new situations.

8.2.2. Design of the experimental component of the Problem

We started the development of the Problem with the experimental aspect, as this was to be the main component and the medium through which the thermal physics would be studied. We wanted the students to design their own experimental method to develop an understanding of the experimental design process and an appreciation for the importance of consistency and accuracy.

As a result of this we needed an experiment that:

- Enabled students to gain an understanding of the heat transfer through radiation
- Allowed them to obtain and curve fit their own data
- Was simple enough for students to develop their own method
- Didn't require specialised equipment, as there were ten set ups required and the practical was being carried out in the PBL classroom

During the research into the topic of radiation, one of the facilitators discovered an experiment based on the heating and cooling of two differently coloured surfaces[1]. We decided to adapt this experiment to suit our own needs, as it was simple, something the students could design themselves, didn't require specialist or expensive materials and included the topic of thermal radiation.

8.2.3. Development of the experiment

In this section, the development of Problem Six is discussed in detail. The design of the Problem was similar to going through the PBL process itself; we started with a problem that we needed to find a solution for and worked through it. We decided that we would design our own experimental set up using the equipment that the students would most likely request (see Figure 8.1). We made many experimental procedure changes from the first version to the final one in order to obtain reliable data. We carried out the experiment for the first time using the set up shown below in Figure 8.1. We set the hot plate at a medium temperature setting and exposed a silver surface and a blackened surface to the heat. The data were logged and uploaded into Excel, as shown in Figure 8.2.

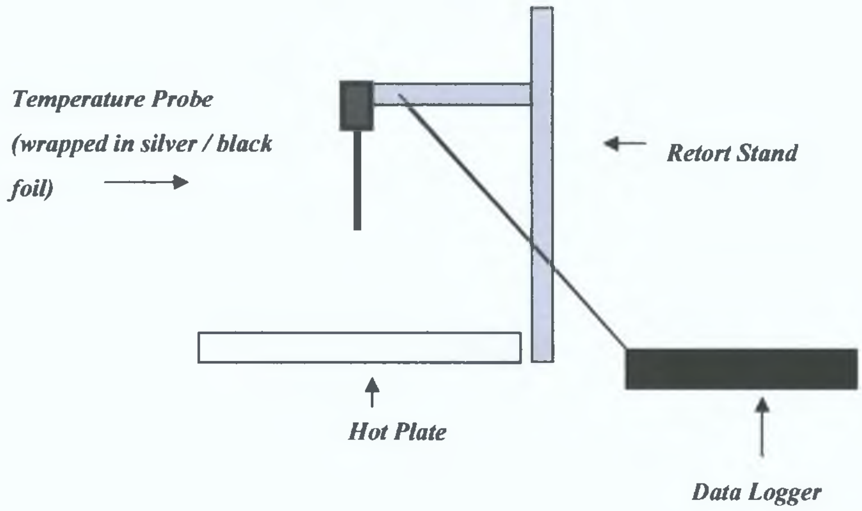


Figure 8.1. First experimental set up.

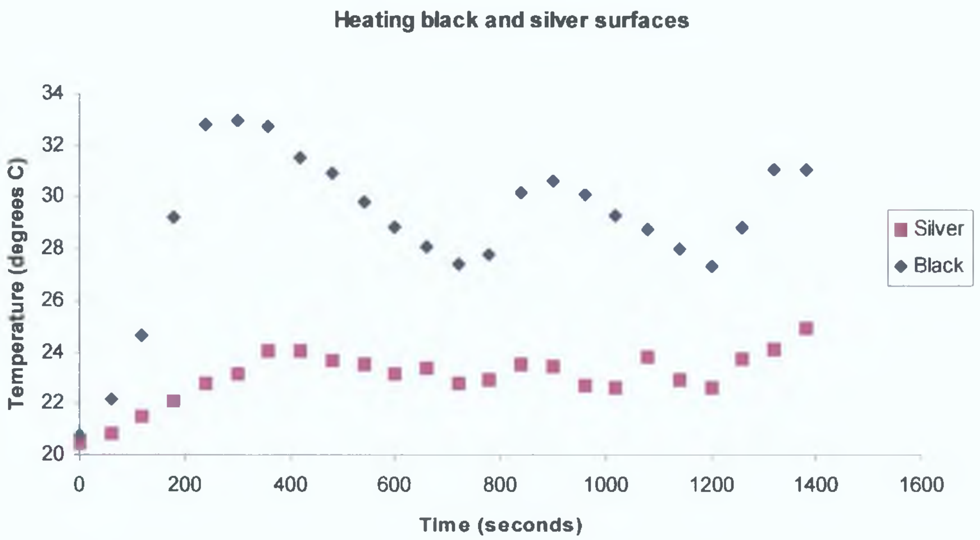


Figure 8.2. *Heating curves for blackened and silver surfaces obtained using the experimental set up in Figure 8.1.*

We repeated the experiment once more and we obtained the same type of incorrect results. We then thought that pockets of air in the aluminium foil may be causing the effect, so we repeated the experiment again with the probe uncovered, however, the same type of graph resulted. We also collected data as the probes cooled (see Figure 8.3) and these showed the expected results, a decrease in temperature over time until thermal equilibrium was reached, with the black surface cooling more quickly. This led us to think that the difficulty must lie with the heating equipment since the cooling curves were correct. After some investigation of the equipment we discovered that the hot plate was fitted with an automatic switch off once it had reached the required temperature. This explained why the graphs showed successive rises and falls in temperature.

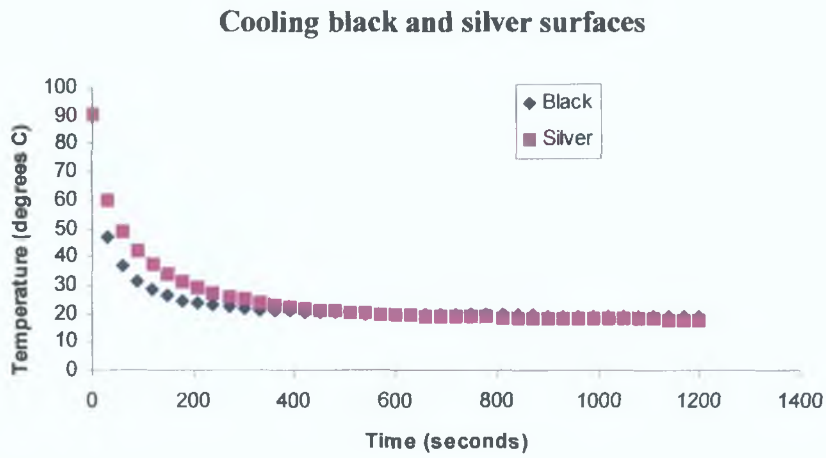


Figure 8.3. *Cooling curves for blackened and silver surfaces obtained using the experimental set up in Figure 8.1.*

We then attempted the experimental procedure for a third time replacing the hot plate with a lamp to ensure a constant heat source. As it was only a test to see if the data obtained would improve, we heated just the silver probe. The resultant graph was smoother than the one obtained using the hot plate. However, it still showed increases and decreases in the temperature over time (see Figure 8.4).

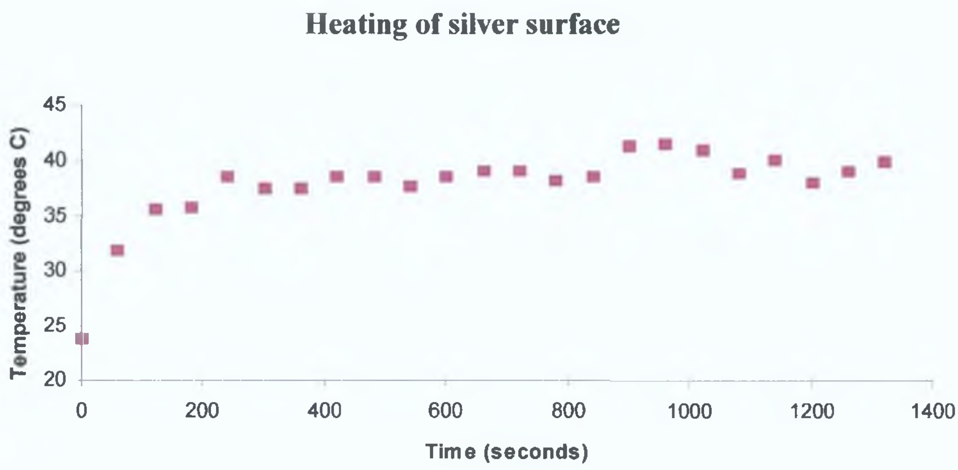


Figure 8.4. Heating curve for a temperature probe heated by a lamp.

We thought that convection currents within the room might have caused the decreases in temperature during the heating. In order to combat this effect we covered the probe with a white Styrofoam cup. This meant that although convection currents would be set up inside of the cup, it would eliminate the temperature probe from being effected by those in the rest of the room. Styrofoam was chosen, as it is an insulator and so lessened the heat exchange between the inside of the cup, where the probe was and the surroundings. This experimental set up (see Figure 8.5) resulted in a much smoother curve as shown in see Figure 8.6.

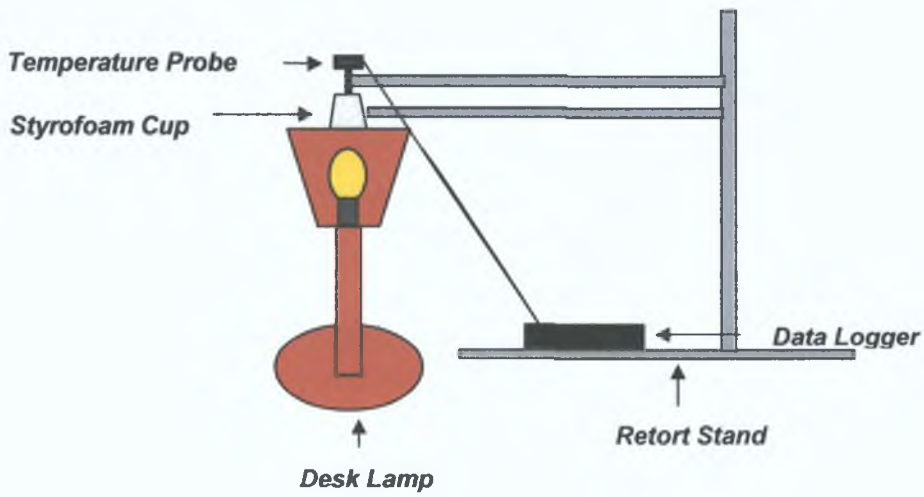


Figure 8.5. Final experimental set up.

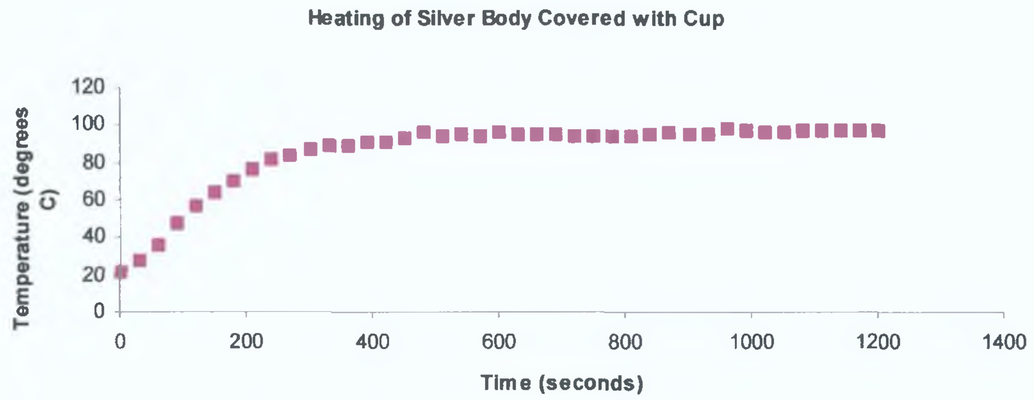


Figure 8.6. Heating curve for a temperature probe covered by a Styrofoam cup and heated by a lamp.

We decided that in order to minimise differences in amount of material wrapped around the probes it would be best to wrap one probe in aluminium foil, log its change in temperature when heated and when cooling and then to spray paint the same piece of foil black and to carry out the experiment again. So, using the experimental set up described above (see Figure 8.5), the rise in temperature of the silver body when heated and decrease when cooled was recorded three times. The graphs were plotted and then compared against each other, see Figures 8.7 and 8.8 below.

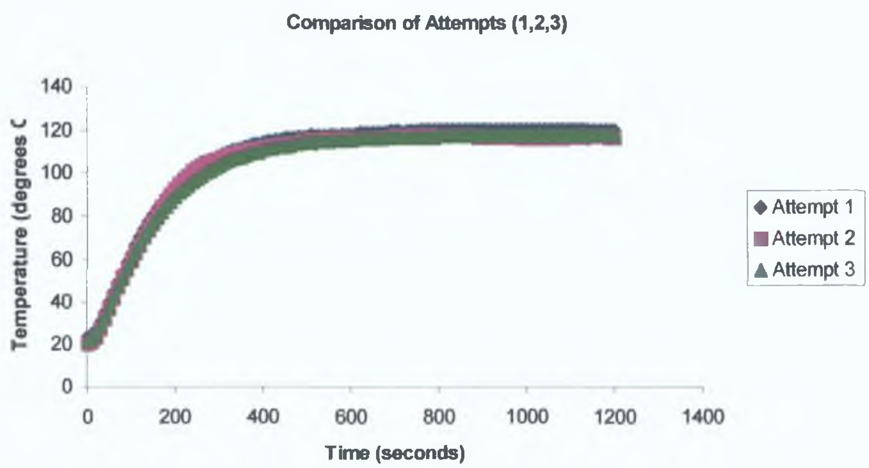


Figure 8.7. Heating curves for silver surface using the experimental set up in Figure 8.5.

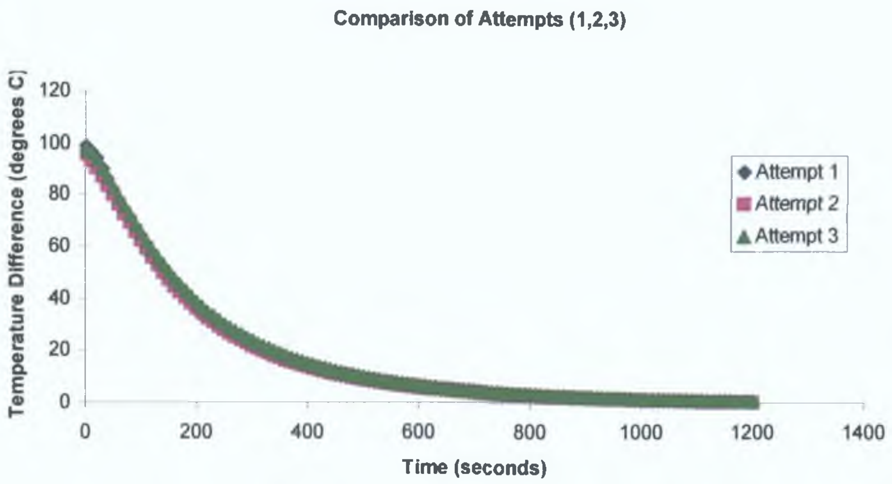


Figure 8.8. *Cooling curves for silver surface obtained using the experimental set up in Figure 8.5.*

As can be seen from Figures 8.7 and 8.8 the experimental method was repeatable and was yielding the expected results. However, inspection of Figure 8.7 shows that the rate of temperature increase ramps up in the first minute. This is due to the lamp heating up after switching it on. Hence we repeated the experiment with a pre-warmed lamp, the results can be seen in Figure 8.9. When this is compared to the heating curves that we took using a non-preheated lamp (see Figure 8.7) it can be seen that the probe was receiving thermal energy from the lamp as it heated, thus in order to ensure a constant heat supply to the probe we was decided that the lamp should be preheated for twenty minutes before the experiment was begun.

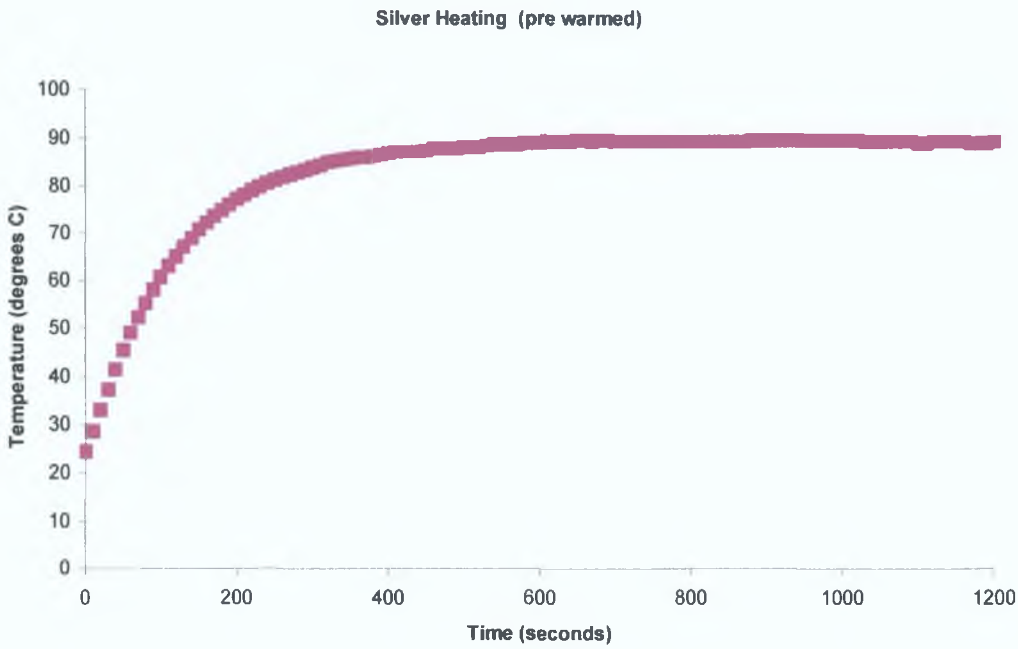


Figure 8.9. *Heating curve for silver surface obtained using the experimental set up in Figure 8.5 with a pre warmed lamp.*

We then decided to examine the cooling curves to determine if the lamp being left on as the cooling data was taken was having an effect. We discovered that as the lamp was being left below the probe as it cooled it was still supplying the probe with heat. So we changed the experimental procedure by removing the lamp from underneath the probe as it was cooling. The graph below in Figure 8.10 shows two cooling curves from data taken with the lamp underneath the probe as it cooled and one taken as the probe cooled without the lamp underneath.

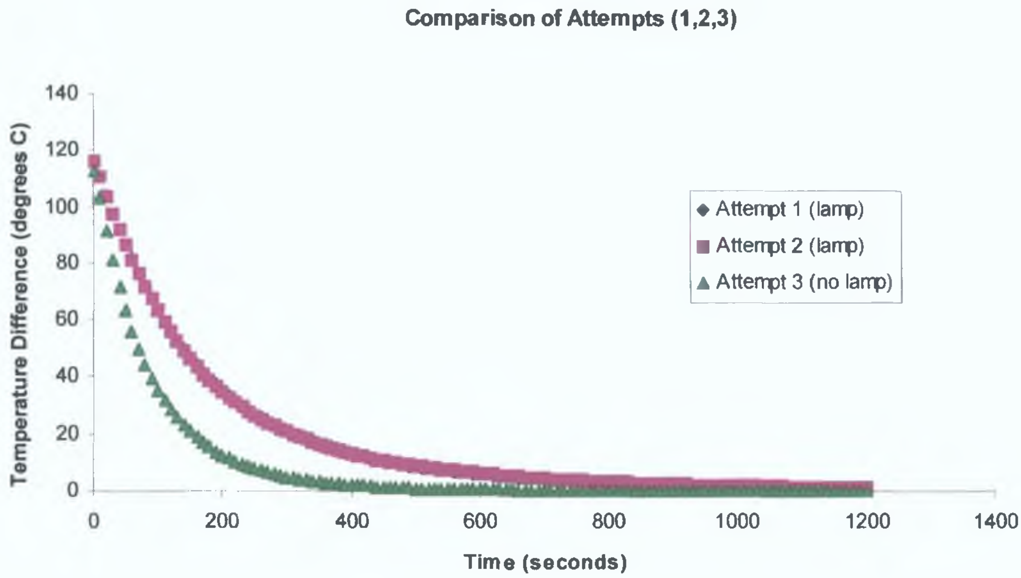


Figure 8.10. Cooling curves for silver surface obtained using the experimental set up in Figure 8.5 with and without the lamp underneath.

The final experimental procedure was as follows:

- The data logger was fitted with a temperature probe and set to measure the temperature every ten seconds over a twenty minute period.
- The probe was wrapped in silver foil and clamped into a retort stand.
- A white Styrofoam cup with a small hole in the bottom was placed upside down over the bulb of a desk lamp, which had been on for fifteen minutes.
- The temperature probe was inserted through the hole in the cup until it rested about half a centimetre above the lamp bulb.
- The data logger was started and the increase in temperature over twenty minutes was recorded.
- After twenty minutes the data taken was uploaded to a PC, while the lamp was left on.
- The data logger was then reconnected to the temperature probe and the cup was clamped in position using another retort arm.
- The lamp was then turned off and removed from underneath the cup.
- Once again the temperature was recorded over a twenty-minute period and the data uploaded onto PC.

- The foil was left around the probe and was spray-painted black.
- It was allowed to dry fully and the procedure was repeated with this black coloured body rather than the silver coloured one.
- Temperature versus time graphs were plotted for the heating and cooling of both the black and the silver bodies.
- The heating curves for the black and silver bodies were then plotted together for comparison purposes and the same was done for the silver ones, they are shown below in Figures 8.11 and 8.12.

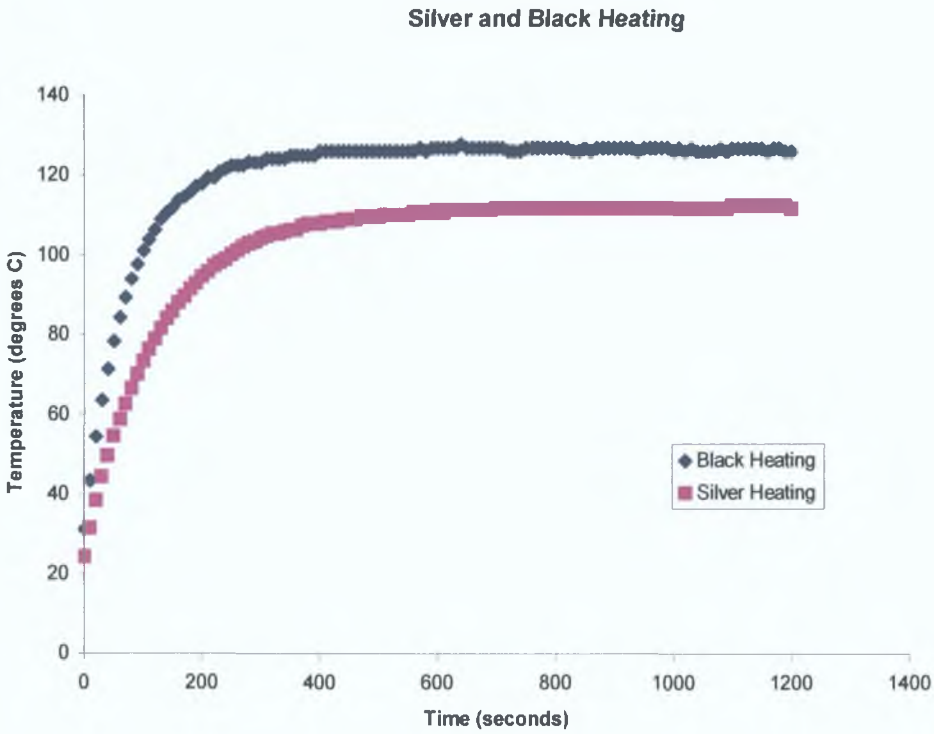


Figure 8.11. *Heating curves for silver and black surfaces obtained using the experimental set up in Figure 8.5.*

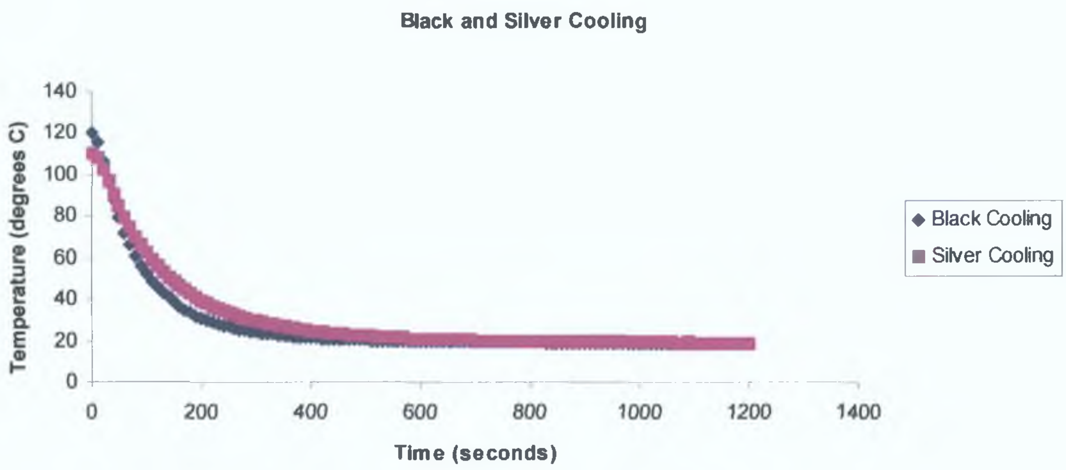


Figure 8.12. *Cooling curves for silver and black surfaces obtained using the experimental set up in Figure 8.5.*

Through experiencing the design process of the experiment ourselves we were able to determine those difficulties that may arise when the students were carrying out the experiment. Rather than limiting students by providing a specific set of equipment we decided to have a range of basic equipment available to them and provide them with anything extra that they required for their method. Through this they would develop an understanding of the importance of experimental design, as they would have to discover their own methods of ensuring reliability and repeatability for example, ensuring the lamp was heated for the same amount of time for each set of readings and placing it the same distance away from the probe.

8.2.4. Research into the concepts involved in Problem Six

Once we had decided on the concepts that we wanted students to study and developed the experimental component of the Problem, we had to choose a suitable topic. After some thought, we decided that insulation may be a good subject, as the concept that the Problem was to deal with was heat transfer.

While completing research into insulation we discovered that some forms of insulation have a thin coating of metal on their surface to prevent heat transfer through radiation[2,3]. We thought that this would be an ideal way of introducing the Problem and encouraging the students to think about heat transfer through radiation, as students had already studied insulation in Part Three of Problem One. The fact that the topic was "real world" was also advantageous as it allowed us to introduce a reason for carrying out the experiment. The Problem is shown in Box 8.1.

Thermal Physics – Problem Six

Part One

You are working in the research and development department of an insulation manufacturer. The current products that the company produce are successful in preventing heat transfer through conduction and convection, but not very effective at preventing heat transfer through radiation. You have been assigned the task of adapting one of the products in order to make it capable of preventing heat transfer by all methods. What factors will you need to consider when choosing the material / materials for your insulation?

Part Two

After careful consideration you decide that coating the original form of insulation in a thin layer of metal would be the best option. You've heard that aluminium foil is often used for this purpose and are considering using it yourself. Why is aluminium a good choice of material?

Now that you've chosen the material, you want to investigate the effect of different surface colours on its effectiveness at reducing heat transfer through radiation. You decide to examine the heating and cooling of unmodified aluminium and aluminium that has been painted matt black. Develop and carry out an experiment that will enable you to study the heating and cooling of these two types of aluminium.

Part Three

Now that you have heating and cooling data for silvered and blackened aluminium you need to analyse it in order to determine which should be used as the insulation material. Develop a mathematical model to approximate the heating and cooling of the foil and use it to curve fit your data. Determine the ratio of emissivities of Aluminium and black paint.

Box 8.1. Problem Six of the PBL thermal physics module.

8.3. Students' response to Problem Six

8.3.1. Comments on Part One

We designed Part One of the Problem to serve as an introduction and to enable students to think about heat transfer through radiation. The fact that students have already experienced the concepts of insulation and heat transfer in previous Problems means that they have some previous knowledge and so this part of the Problem instils confidence in them. Through asking the students what factors need to be considered when trying to prevent heat transfer through radiation we help them to think about things that they will need to consider in Part Two when designing their experiment, such as ensuring the same thickness and area of foil for both types of aluminium.

8.3.2. Students' answers to Part One

All groups thought about heat transfer and the properties of matter that determine their rate of heat flow, such as U values and emissivity. Some students also thought about factors unrelated to the thermal properties of the material such as cost, safety and location. A representative answer to this part of the Problem is shown below in Box 8.2.

In order to prevent all three types of heat transfer, we need to consider what each method of heat transfer depends on. These are the factors that need to be considered when choosing the material(s) for insulation.

Conduction depends on:

1. The material (some materials conduct well (metal), others poorly (plastic))
2. Thickness of material (the thinner it is, the better the conduction)
3. Surface area (larger area, better conduction)
4. Temperature difference across the material (bigger the difference, the better the conduction)

Convection depends on:

1. The material (some materials absorb and move more heat (water) while others don't absorb and move much heat (air)
2. The motion of the material (such as the currents in air, moving air carries away heat faster than motionless air)

Radiation depends on:

1. The temperature of the object (the hotter it is, the more it radiates)
2. The surface area of the object (smaller the surface area the greater the radiation)
3. The emissivity of the object. (Emissivity is the ability of the object to absorb and emit thermal radiation. Dark colours have a high emissivity while light colours have a low emissivity) emissivity is a number between 0 and 1.

Box 8.2. *Representative answer to Part One of Problem Six of the PBL thermal physics module.*

It is evident from this answer that Part One of the Problem has encouraged these students to think about the methods of heat transfer. They list the factors that determine the effectiveness of materials to transfer heat through conduction, convection and radiation. Although this particular group did not give other considerations such as cost and safety, it is clear that they have put thought into the answer and gain an understanding of heat transfer through completing the Problem.

8.3.3 Comments on Part Two

Part Two of the Problem begins with a simple question, which serves as an introduction and encourages the students to think about why aluminium is suitable as insulation against heat flow through radiation (see Box 8.3 for a representative answer). The students are then given a "real world" reason to investigate the effect of colour on heat transfer by radiation. They are asked to decide if the metal coating on the insulation should be black or silver. In order to do this they are required to design and carry out an experiment. This part of the Problem encourages students to think about experimental design, as they are not given a list of equipment or specific instructions, they are entirely free to develop their own experimental method. Through developing the experiment students should think about the best methods of ensuring that they are concentrating on heat transfer through radiation as opposed to conduction and convection, and how to minimise errors and ensure consistency. This part of the problem also requires students to transfer their previous knowledge of heat transfer and to use their group work skills to best advantage in order to maximise their efficiency.

8.3.4. Students' answers to Part Two

Part two

Aluminium foil is a good choice of material because:

1. Barrier properties (light, gases, oils and fats, volatile compounds and water vapour)
2. Reflectivity and Conductivity (in this case only reflectivity is relevant since it will act as an insulator)
3. Temperature resistance from extreme changes
4. Strength and durability
5. Easy to laminate or coat if desired.
6. Flexibility.
7. Formability (can be dead folded perfectly).
8. Long term insulation against moisture and naturally occurring corrosive elements.
9. Stops access to oxygen (good for firewalls/ fireproof doors etc.)
10. An abundant material, cheap and available.
11. Decorative potential (matt or brilliant surface).
12. Non-toxic and safe to use.
13. Low weight.
14. Can be recycled (good for environment).

***Box 8.3.** Representative section of an answer to Part Two of Problem Six of the PBL thermal physics module.*

As can be seen from the above student answer the introductory question of Part Two encouraged students to think about the properties of aluminium that made it suitable for use an a insulation material. Asking the students this question helped to ease them into the experimental component of the Problem. All of the students had some knowledge of aluminium and were able to answer the question right away; as a result it instilled confidence in students.

The difficulty of students not thinking about experimental design became apparent as soon as students began the experimental component of Part Two of the Problem. Rather than thinking about what they needed to analyse and how best to obtain appropriate data, students either looked at how others were setting up, or just examined the equipment provided and chose a set up from that. As a result of this most groups ended up with the same experimental set up, which was to wrap the foil around the Styrofoam cup, within which the temperature probe was placed. However, as facilitators talked to each group and questioned them on their method students realised that their experimental methods needed more thought. They were asked questions about why they chose to wrap foil around the cup and place the probe inside; this led them to think about heat transfer from the foil to the cup and which methods are involved. As a result of this students realised that they needed to alter their set up to try and ensure they were looking at heat transfer through radiation and many of them did. Boxes 8.4 and 8.5 below show representative sections of two groups' explanation of their experimental method.

The temperature probe was inside the cup for all three trials.
A 25W bulb was used for each and the lamp was a fixed distance from the cup each time.
The aluminium foil covered the cup in exactly the same way for both the silver trial and the black trial as we merely sprayed the silver foil black afterwards. This ensured a fair test, enabling accurate comparison of the results.

Box 8.4. *Representative section of an answer to Part Two of Problem Six of the PBL thermal physics module.*

This section of the students' answer shows that they have put some thought into ensuring consistency and accuracy of results. The state that they place the lamp the same distance away each time the experiment takes place and that they ensure the bulb is the same strength. These students actually state explicitly that they carried out these measures to ensure that they could compare the results of their experiments.

Heating

1. We cut out two squares of aluminium of exactly the same size and then paint one of them with black matt paint.
2. We placed the temperature probe in a hole in the base of a cup.
3. We wrapped the silvered aluminium square around the probe (shiny side facing out) and placed the open end of the cup up to the lamp. We chose to do it this way because there wouldn't be conduction through the cup, only through the aluminium and the only convection affecting the temperature is in the air within the cup. Therefore the main process of heat transfer between the probe and the lamp would be radiation. ✓
4. The temperature probe was connected to a data logger which measured the temperature every second for 3 minutes, giving this graph

5. We then did the same for the blackened aluminium, with the black side facing outward, making sure that it started at the same temperature that the silvered aluminium started at.

Did you also ensure it was at the same distance away and roughly the same surface area was exposed?

Box 8.5. Representative section of an answer to Part Two of Problem Six of the PBL thermal physics module.

Paragraph three of the answer in Box 8.5 shows that students have considered the best method of examining thermal radiation to the exclusion of conduction and convection. These students have also thought about keeping the surface area of the foils the same, which demonstrates that they have put some thought into consistency in their design.

Although they don't explicitly state that they placed the lamp at the same distance from the foil for all experiments it was apparent from observations during tutorials that they were. It is evident from both these students' answers that Part Two of the Problem was successful in enabling them to develop an understanding of the importance of ensuring consistency in experimental design.

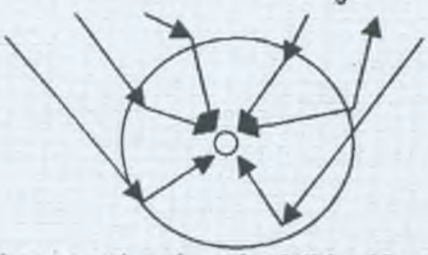
Although these answers show that some groups did put thought into experimental design, not all did so. The lack of thought about the experimental set up was evident from the students' reports. Only one group out of eight, explicitly showed that they had thought about how they could minimise heat transfer to and from the foil by conduction and convection, with only three groups giving an explanation of why they chose the set up that they did. Some students continued their experiment using the original set up of foil around the Styrofoam cup and as a result obtained incorrect results. However, students learned a lot from their mistakes, when writing the reports they realised that they could have put more thought into the initial procedure. When the experiments didn't go as expected, students learned from analysing their results; an example taken from a student report is given below in Box 8.6.

Straight away we noticed that the highest temperature that the black aluminium reached was lower than that of the unmodified aluminium foil. This was completely unexpected because looking at the properties that affect the heat transfer through radiation then most of the radiation should be reflected away and in the case of the black aluminium, most of it should have been absorbed and so should have reached a higher temperature.

This puzzled our group and so we decided to run the experiment again, but the results we obtained were exactly the same, the black coated reached a lower temperature than the unmodified foil. We then realised why this was happening by looking at the set-up of the experiment.

We had set-up the probe in the centre of the cup, not placed on the actual foils, this meant that we were actually measuring air temperature, not the temperature of the foils.

Therefore when the light source was shining in on the pure aluminium foil, most of it was reflected back and probably most of it hit the temperature probe meaning that the temperature would go higher, than the black aluminium.



As the radiation entered the cup it hit the pure aluminium foil and was reflected back onto the probe in the centre of the cup.

Because of the radiation the probe heated to a higher temperature than it would have if the probe were placed on the foil itself.

For the black aluminium, the opposite would happen, there would be a high factor of the radiation that got absorbed by the black aluminium foil (because a black surface is a bad reflector and a good absorber of radiation), therefore there would be a lot less reflected radiation shining onto the probe, so it would reach a lower temperature than the pure aluminium.

Therefore it proved that the best coating to use to prevent heat transfer through radiation is to use the aluminium coated insulation.

Box 8.6. *Student analysis of their experimental results from Part Two of Problem Six.*

It is evident from these students explanation that they have put thought into what results they should have obtained before carrying out the experiment (paragraph 1). Once they realised that their results seemed to be contradictory to theory, they carried out the experiment again to check if this was just circumstantial. When the same results were obtained they looked for difficulties with their experimental design. Through this they realised that their set up was inappropriate as it was measuring air temperature rather than that of the aluminium foil itself. There is evidence that they have developed an understanding of thermal radiation, they explained why the silver foil resulted in a higher temperature.

To encourage students to think about the most appropriate way to set up the experiment rather than just acting on their first thought, requiring them to give a detailed description of their set up and how and why they are choosing to complete the experiment in this way before supplying them with any equipment would be beneficial and something that will be done the next time the Problem is delivered. This type of exercise would also be useful for combating students setting up their experiment in ways that they have seen other groups do. In order to ensure that students put more thought into the experimental design before starting the procedure, this part of the Problem was re-worded as shown below in Box 8.7.

> *After your research into materials you decide that aluminium would be the best choice. However, you first want to investigate the effect of different surface colours on its effectiveness at reducing heat transfer through radiation in order to decide if unmodified aluminium or aluminium that has been painted matt black should be used. Write a report for your manager explaining why you've chosen aluminium as your coating material as well as outlining your planned method of studying the heating and cooling of the two types of aluminium. Your report should include the reasons why you've chosen the particular type of experimental set up that you have and any relevant information about how you will ensure the reliability of the data you hope to produce.*

Box 8.7. *Reformulated Part Two of Problem Six of the PBL thermal physics module.*

8.3.5. Comments on Part Three

When designing this Problem, we wanted to include a question that would develop students' mathematical skills as well as their ability to analyse graphs. These skills are required to answer Part Three of the Problem. Students are required to develop a mathematical model to describe their data. Through this we hoped that they would add to the modelling skills that they had acquired from previous Problems and develop an ability to analyse graphically represented data.

This part of the Problem is quite challenging and so it is a little more prescriptive than the others. Students are told that they need to develop a mathematical model in order to curve fit their data and from this they can determine the ratio of the emissivities. Although this means that the problem is less open ended than it should be, it was necessary to enable students to be able to solve it. We were willing to lose some of the PBL element in order to have students practice their graphing and analysis of data skills. If the question had been less prescriptive students would not have known where to begin and certainly would not have time to solve it.

In order to fit a curve to the graph of the rise in temperature over time students need to develop an expression to represent the heat flow. They must recognise that:

- The heat given by the lamp is constant, H_{in}
- Radiation from the lamp is the only source of thermal energy
- The heat flow out of the surface is proportional to the temperature excess above room temperature (which students have seen in Problem One)

In order to model the heat flow into and out of the silver or black foil, we used Newton's Law of Cooling (equation 1) and followed the steps outlined below:

$$H_{out} = \beta(T - T_S) \qquad (1)$$

The net heat flow is thus given by equation 2:

$$H = H_{in} - H_{out} = H_{in} - \beta(T - T_S) \tag{2}$$

The rate of change in temperature due to any net heat flow is given by.

$$H = mc\left(\frac{dT}{dt}\right) \tag{3}$$

From equations (2) and (3) we get:

$$mc\left(\frac{dT}{dt}\right) = H_{in} - \beta(T - T_S) \tag{4}$$

Then letting $A = \left(\frac{H_{in} + \beta T_S}{mc}\right)$ and $B = \frac{\beta}{mc}$, we can write

$$\frac{dT}{dt} + BT = A \tag{5}$$

In order to solve this we need to solve the homogeneous differential equation

$$\frac{dT}{dt} + BT = 0 \tag{6}$$

and then add the particular solution. The general solution to equation 5 is:

$$T = C.e^{-Bt}$$

and a particular solution is:

$$T = \frac{A}{B} = \frac{H_{in}}{\beta} + T_S$$

Therefore the solution of the non-homogenous differential equation is:

$$T = \frac{H_{in}}{\beta} + T_S + Ce^{-Bt} \tag{7}$$

To eliminate C, look at the initial conditions; at the start of the heating process the temperature of the body is equal to the temperature of the surroundings. In other words, at $t=0$, $T = T_S$, and so

$$C = \frac{-H_{in}}{\beta} \tag{8}$$

Substituting equation 8 back into equation 7 we obtain:

$$T = T_S + \frac{H_{in}}{\beta}\left(1 - e^{-Bt}\right) \tag{9}$$

Both H_{in} and β (and therefore, B) are unknown; we cannot yet fit a curve with independent parameters H_{in} and β. However, we can look at the rate of change of temperature by differentiating equation 9:

$$\frac{dT}{dt} = \frac{H_{in}}{\beta} \times B \times e^{-Bt} = \frac{H_{in}}{mc} \times e^{-Bt} \tag{10}$$

Approximating $\frac{dT}{dt}$ by $\frac{\Delta T}{\Delta t}$, we can curve fit the data to obtain H_{in} and B independently as shown in Figures 8.13 and 8.14. As we expected B is larger for the black coloured body ($B = 0.0116$) as it heats up and cools more quickly than the silver ($B = 0.0084$). Note that the constant B is not related in a simple way to the emissivity, as we have used Newton's Law of Cooling; however, the data can also be modelled using the Stefan Boltzmann Law, which is described at the end of this section.

Alternatively, rather than using equation 10 to curve fit, students could plot $\ln\left(\frac{\Delta T}{\Delta t}\right)$ versus t, and determine H_{in} and β from the slope and intercept:

$$\ln\left(\frac{\Delta T}{\Delta t}\right) = \ln\left(\frac{H_{in}}{mc}\right) - Bt \qquad (11)$$

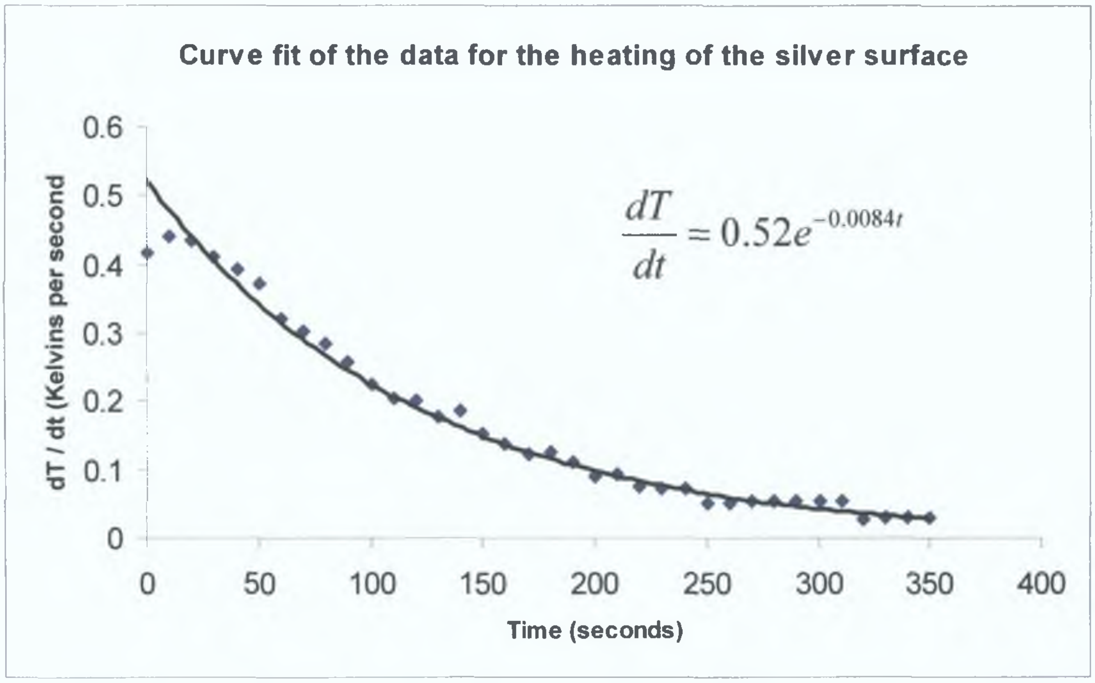


Figure 8.13. *Curve fit used to find constant B, for the heating of the silver surface*

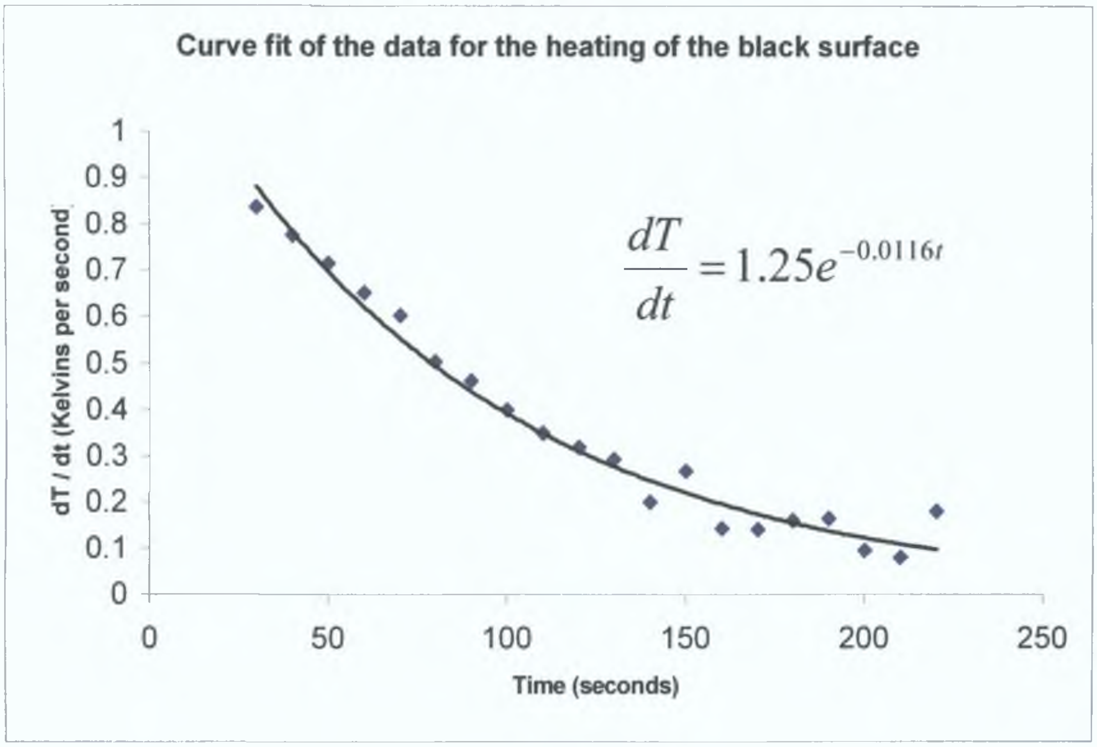


Figure 8.14. *Curve fit used to find constant B, for the heating of the black surface.*

The same method can be applied to curve fitting and obtaining a value for the constant B for cooling. The difference is that, when the lamp is moved away from the object, $H_{in}=0$, so that equation 7 becomes:

$$T = T_S + Ce^{-Bt} \qquad (12)$$

At $t=0$, $T = T_{max}$, so

$$T = (T_{max} - T_S)e^{-Bt} + T_S \qquad (13)$$

In this simpler problem, we can curve fit straight away:

$$(T - T_S) = (T_{max} - T_S)e^{-Bt} \qquad (14)$$

The curve fits completed using equation 14 are shown in Figures 8.15 and 8.16. The values for the constant *B* are similar to those found for the heating data and once again *B* is higher for the black body (B = 0.0101) than the silver body (B = 0.008), as expected.

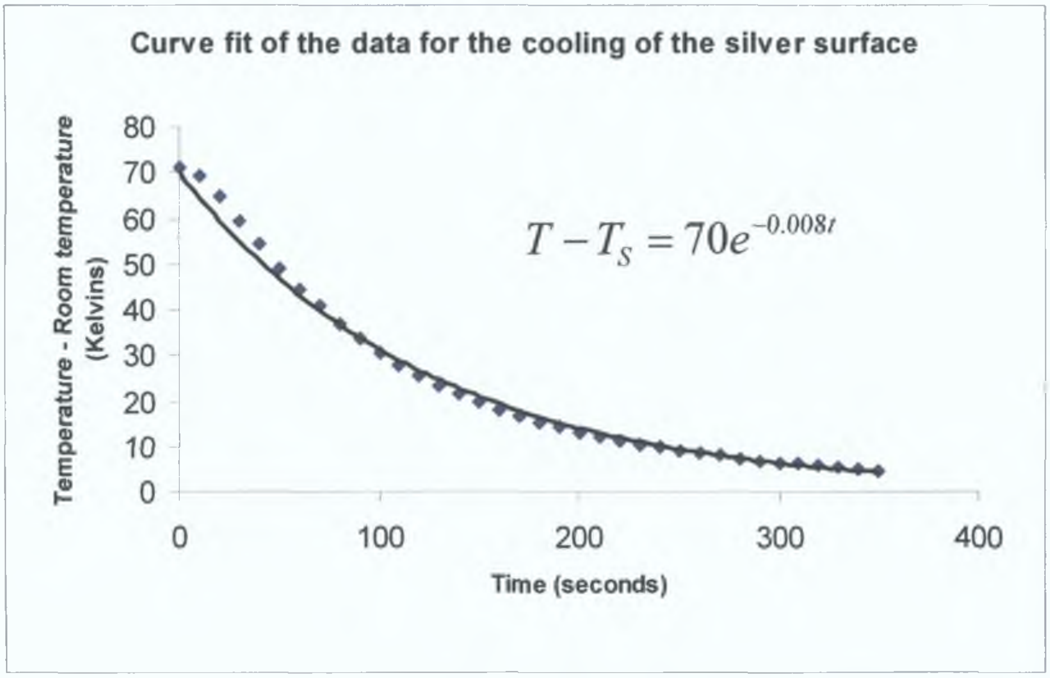


Figure 8.15. *Curve fit used to find constant B, for the cooling of the silver surface.*

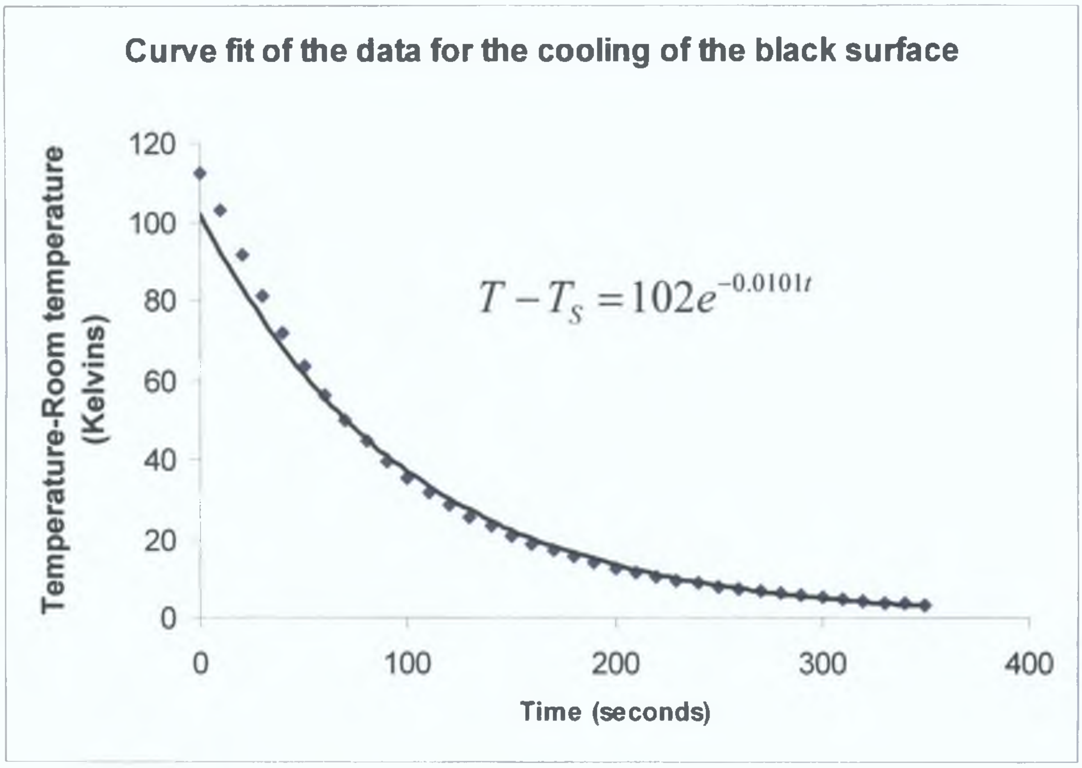


Figure 8.16. *Curve fit used to find constant B, for the cooling of the black surface.*

Once again, as with the heating data, students could alternatively curve fit linearly. This can be done by expressing equation 14 as a linear relationship (equation 15) and plotting $\ln(T - T_S)$ against *t*.

$$\ln(T - T_S) = \ln(T_{max} - T_S) - Bt \qquad (15)$$

We decided that we would also model the heat flow using the Stefan-Boltzmann equation, (see equation 14 below)

$$\frac{dQ}{dt} = \sigma \cdot e \cdot A\left(T^4 - T_S{}^4\right) \tag{14}$$

where σ = Stefan-Boltzmann constant, e = emissivity, A = surface area, T = temperature, T_S = temperature of the surroundings.

We did this in case it arose that students used this equation to model heat flow, as it describes heat flow through radiation and this is mentioned in Part One of the Problem.

We determined the emissivity values using the Stefan-Boltzmann equation, (see equation 14), by the method outlined below.

The heat needed to raise the temperature of the foil is given by:

$$Q = mc(T - T_0) \tag{15}$$

where m = mass, c = specific heat capacity, T = final temperature, T_0 = initial temperature.

Therefore by substituting the expression for heat (equation 15) into equation 14, we can approximate an equation for the rate of change of temperature with time, equation 16.

$$\frac{d}{dt} mc\left(T - T_0\right) = \sigma\, eA\left(T^4 - T_S{}^4\right)$$

$$\frac{dT}{dt} = \frac{\sigma\, eA}{mc}\left(T^4 - T_S{}^4\right) \tag{16}$$

In order to determine the ratio of the emissivities, we plotted $\frac{dT}{dt}$ against $\left(T^4 - T_S{}^4\right)$, this resulted in a line with slope equal to $\frac{\sigma eA}{mc}$. This can be done for both the heating and the cooling curves. Since all the variables except the emissivities are the same for both foils, their ratio can be found from the ratio of the slopes.

We calculate the ratio of the emissivities using our heating data for the silver and black foil. By taking the ratio of the slopes of the graphs in Figures 8.17 and 8.18 we determined that the emissivity of the silver foil was two thirds that of the black foil. This is what was expected as the black is a better emitter and absorber of radiation and so should have a higher emissivity value than the silver.

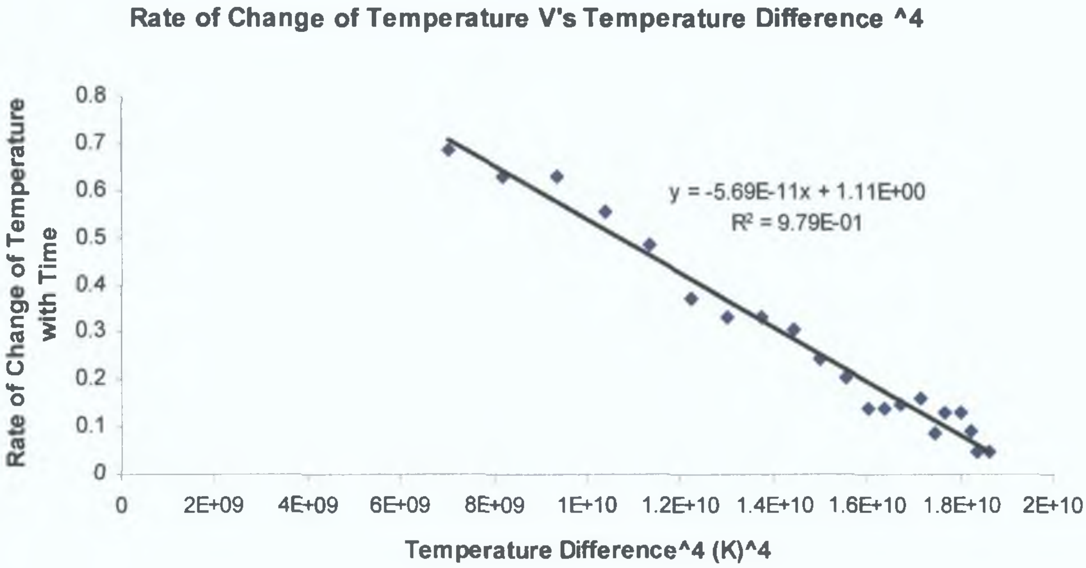


Figure 8.17. *Curve fit for the heating of the black surface obtained by applying the Stefan-Boltzmann Law.*

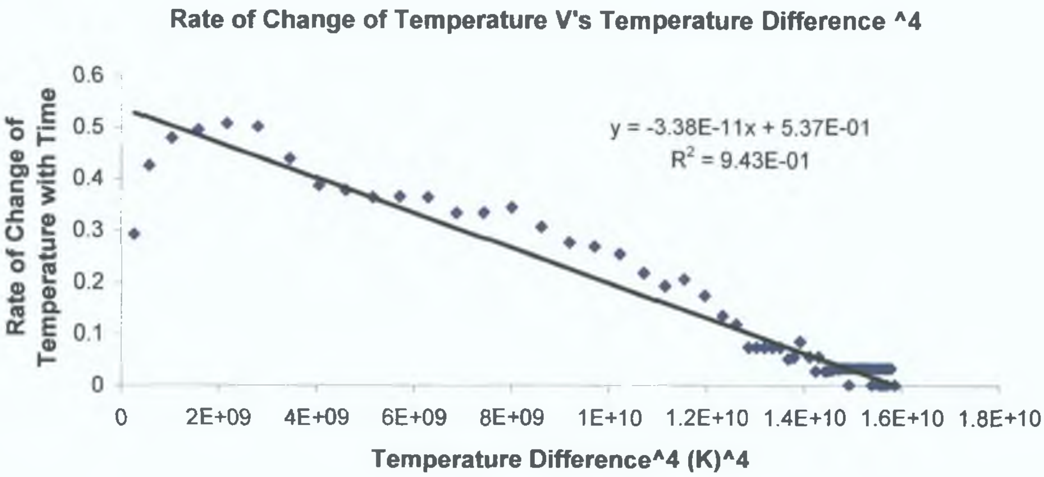
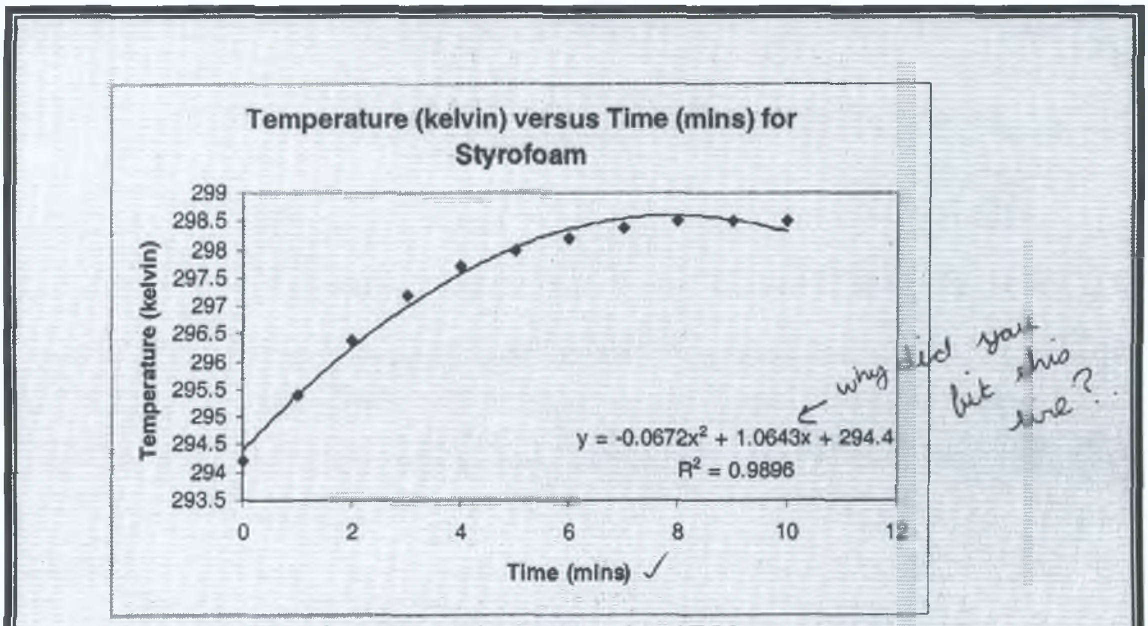


Figure 8.18. *Curve fit for the heating of the silver surface obtained by applying the Stefan-Boltzmann Law.*

8.3.6. Students' answers to Part Three

Students found this part of the problem very challenging. One of the reasons for this was that they didn't have a lot of time to solve it or discuss it with facilitators. It was evident during tutorials that students were not considering how to make the best use of their time. We gave students the Problem in its entirety and so they were aware from the beginning that they needed to curve fit the results of their experiment. In spite of this, all groups carried out the experimental component together. It would have been more time efficient for half of them to analyse the first set of results once they were taken, while the others continued with the experimental work. This lack of time management resulted in students not having enough time for Part Three of the problem. Although we felt that the students would be able to apply the Stefan-Boltzmann equation to their data, we knew that they would require guidance, as that they have no previous experience of applying mathematical models.

A common error, made by half the groups, was to curve fit their heating and cooling graphs with polynomials as these seemed to fit. This can be seen below in Box 8.7. However, there is no justification for this; students seem to see the graphs and mathematics as being removed from the actual physics. This is surprising, as the students had all previously studied curve fitting using Excel in another module. It is obvious from students' responses to Part Three of this Problem that they were not able to transfer any of the knowledge and skills that they gained from this module.



Graph1: Temperature as a function of time as Styrofoam was heated

***Box 8.7.** Student graph from Part Three of Problem Six.*

Six out of the eight groups attempted to use the Stefan-Boltzmann equation to develop a model for the heating and cooling of the foil, however only four of these groups succeeded in establishing what they needed to plot to determine the ratio of the emissivities (see Box 8.8) and only one group out of this four actually managed to obtain it.

In this part of the problem we were asked to develop a mathematical model so as we could compare the ratios of the emissivities of silver and blackened aluminium. Our starting point for this was equation 1. why?

$$H = Ae\sigma T^4 \qquad \text{Equation 1}$$

Where H is the rate of heat flow, A is the surface area of the aluminium foil T is temperature in degrees Kelvin and σ is the Stefan-Boltzmann constant. We subbed in dQ/dt instead of H, as this is the rate of heat flow over time, as we knew time because we had recorded it. Also the temperature was why? expressed as a temperature difference between the room and the aluminium foil. Where Tr in equation 2 is room temperature.

$$\frac{dQ}{dt} = Ae\sigma(T^4 - Tr^4) \qquad \text{Equation 2}$$

Combining equation 2 with equation 3 where m is mass and c is specific heat capacity equation 4 was developed

$$Q = mc(T - To) \qquad \text{Equation 3}$$

$$\frac{d}{dt}mc(T - To) = Ae\sigma(T^4 - Tr^4) \qquad \text{Equation 4}$$

Dividing equation 4 up into two separate differentiable parts gave us equation 5.

$$\frac{d}{dt}mcT - \frac{d}{dt}mcTo = Ae\sigma(T^4 - Tr^4) \quad \text{Equation 5}$$

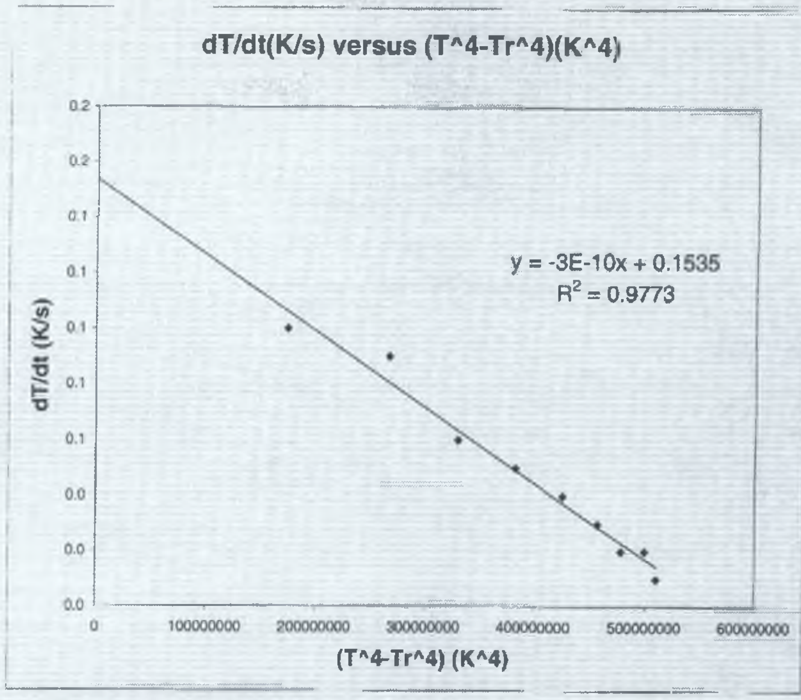
We then developed this into equation 6

$$mc\frac{dT}{dt} = Ae\sigma(T^4 - Tr^4) \quad \text{Equation 6}$$

Upon manipulation we reached equation 7

$$\frac{dT}{dt} = \frac{Ae\sigma}{mc}(T^4 - Tr^4) \quad \text{Equation 7}$$

Equation7 tells us that the rate of change of temperature over time is equal to the surface area of the aluminium x Stefan-Boltzmann's constant x the emissivity divided by the mass x the specific heat capacity of the foil. This is then multiplied by the temperature difference to the power of 4. We determined that a plot of dT/dt against $T^4 - Tr^4$ should yield a straight line graph of gradient k. The precise value of k is outlined in equation 8 below.



Graph 7. *Plot of dT/dt against $T^4 - Tr^4$*

$$k = \frac{Ae\sigma}{mc} \qquad \text{Equation 8}$$

As the surface area, Boltzmann's contant, the mass and the specific heat capacity are all constants k/k would be equal to e/e and thus we could determine the ratio of the emissivities.

They are the same for the silver and black foil but not always the same values.

***Box 8.8** Student answer to Part Three of Problem Six.*

To ensure that students have adequate time to complete this part of the Problem it will be necessary to make suggestions to them on how to manage their time effectively if they seem to be concentrating on Part Two. The fact that students will develop and discuss a suitable method before beginning means that they will have a lot more time for the analysis of the data, as they won't have to redo the experiment as a result of obtaining incorrect data from a poor set up. These changes should result in students dedicating more time to this part of the Problem and as a result, more of them completing it successfully. Part Three will also have to be re-worded slightly (see Box 8.9 below) to accommodate the change to Part Two.

After viewing your report, your manager agrees that the investigation should take place. Carry out the experiment you've developed to study the heating and cooling of the two types of aluminium. Once you have collected your data it needs to be analysed in order to determine which of the foils should be used as the coating material. Develop a mathematical model to approximate the heating and cooling of the foil and use it to curve fit your data. Determine the ratio of emissivities of aluminium and black paint and decide which type to use as your coating material

Box 8.9 *Revised version of Part Three of Problem Six of the PBL thermal physics module.*

8.4. Conclusion

By presenting a simple thermal physics experiment to the students through PBL a large number of extra educational benefits were obtained. Rather than telling students what to do or allowing them to follow instructions, they were given the freedom to come up with their own experimental methods. This enabled students to realise for themselves the importance of modelling physical phenomena and the significance of experimental design. Students gained a deeper understanding of the physics and the experimental procedure in this way. It is evident from the students' answers that they have thought and analysed their methods and results.

References:

1. Ehrlich, R. *"Why toast lands jelly-side down : Zen and the art of physics demonstrations"* Princeton University Press, Princeton, N.J.: 1997
2. Insulation information online: http://www.flasolar.com/rb_faq.php
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Chapter Nine Conclusions

9.1. Introduction

This final chapter reviews how well Problem Based Learning achieved the aims of the thermal physics module. We also examine the skills and knowledge that students developed through undertaking the module. Finally, improvements and further developments to the module are recommended.

9.2.The effectiveness of PBL in achieving the aims of the module

One of the aims of third level education is to develop those skills in individuals that are required in their chosen employment. The many skills required to be a successful scientist include; the ability to communicate well, retrieve information, use technology, research solutions, apply knowledge and work effectively with others. The main purpose of the PBL module was to provide students with an understanding of basic thermal physics while at the same time developing these critical skills. Throughout the module there was observational evidence that these skills were being developed as students worked through the Problems. The PBL module achieved this through providing the students with an opportunity to work as part of a group, carry out independent research, and apply their previous knowledge to solving new problems. In addition to this there was also evidence from the pre and post tests that students were developing a deeper understanding of the thermal physics through completing the Problems.

9.2.1. PBL's impact on improving students' group work skills

It is evident from the research undertaken that Problem Based Learning was effective in developing students' ability to work with others. In answering the Introductory Problem, students listed difficulties with group work as their main concern, however at the end of the module students' answers to the questionnaire indicated that they felt that their ability to work with others had improved after completing the module. Although the issues arising from group work were still considered one of the biggest student concerns after completing the module, there was a significant decrease in the number of students expressing worry about certain aspects of the group work, such as lack of participation. The likely reason for this was that students had experienced these difficulties while completing the module and so had developed methods of dealing with them.

Each of the PBL groups had some difficulty with the group work aspect of the module during its course. Most of the difficulties arose from lack of participation by one or more group members. There were three groups in which this became a major issue. However, each one of these groups gained a lot from having to cope with this situation. Members of each of these groups tackled the problem for themselves, first by speaking to the group members in question. It was when this failed to achieve results that they came to discuss it with a facilitator. Through this discussion, each of the groups developed a strategy to deal with group member participation. All of them decided to tell the students in question that they would lose marks from the group work aspect of the module if they didn't start to complete their share of the work and participate fully in the groups' activities. This was effective in dealing with two of the three groups, however one group still had difficulties. The reason that this group was failing to function properly was the lack of participation by a number of students and personality conflicts within the group. However after a discussion between all members of the group and a facilitator they overcame enough of the difficulties to function at some level. It was evident from these groups' answers to the questionnaire that they appreciate the skills that they had developed through dealing with these difficulties. Despite their problems they would like to complete other modules through PBL.

9.2.2. PBL's impact on improving students' ability to retain and transfer knowledge

The ability of PBL to require students' to transfer previous knowledge to new situations was apparent from the very beginning of the module. In answering Problem One students straight away applied their previous knowledge about heat transfer and thermal equilibrium, even if they were not aware of doing so. Over the course of the module, the use of their previous formal knowledge became more obvious, for example in Problem Three students had to apply what they had learned about the Ideal Gas Law from Problem Two. There were many other instances of this short distance transfer of knowledge, for example students applied what they had learned about heat transfer from Problems One and Four in developing a solution to Problem Six. However, students were not able to transfer knowledge to significantly different problems. This was evident from the students' inability to apply Archimedes Law in the post tests of Problem Two in which some of the situations differed significantly from the one that the students had studied through solving the Problem. Students also had difficulties in recognising the relevance of what they had studied to questions in the final exam, which is further evidence that studying one module through PBL didn't improve students' ability to transfer knowledge to new situations to the extent we would have liked, only those that they recognised as similar to what they had studied.

In relation to the retention of information, there was observational evidence as the module progressed that students were able to retain what they were learning. When students were questioned on topics which they had previously studied relevant to new Problems, they were able to answer. There were also comments from a small number of students towards the examination time that it was easier to revise as they better remembered what was covered during the module from having to research the information and apply it. This was also evident among the students who completed the PBL module during the previous year from comments, which a number of them made indicating that they retained information and knowledge of thermal physics, although they had forgotten most information from other modules completed through lecture. It would be very beneficial to assess the retention of information by giving students an examination after a length of time has passed, for example during the next semesters examinations. It would be even more useful if it were possible to deliver the course again with a lecture control group and then give an examination after six months, this would allow us to compare the effect of PBL and lecture on long-term retention of information.

9.2.3. PBL's impact on improving students' ability to carry out effective research and develop appropriate physical models

During the first PBL tutorial when students were adjusting to the new methodology, not one of the groups went to complete research into the topic of the Problem, which was the PBL methodology. By the second tutorial students were starting to realise that they needed to look up relevant information, for example the temperature at which goldfish die in order to solve Problem One. Through completing necessary research to solve the Problems students' skills developed throughout the module. By the end of Problem Two most groups had designated one person out of the group to complete research as others continued to work on the Problem. As the module went on students started to give more complete references for their information, they learned to source reputable and reliable information and how to recognize what information was necessary and what wasn't.

The PBL methodology also had a large impact on students modelling skills. Before the module, students would have had little experience of this method of solving problems, being more used to solving numerical problems by substituting in given figures. The tendency of students to look for a formula first and "plug in" numbers was obvious from the very first Problem, when students tried this method of determining when the goldfish would die. Initially students found the modelling process difficult but with guidance all groups developed a successful solution to Problem One. Modelling skills were required in each Problem, and the benefits of solving Problems using this method were particularly evident from Problem Four. The fact that students' modelling skills were improving was evident during the module. Once students had completed Problem One they began to develop an understanding of the process, they used their skills in Problem Two to model the heat flow out of the hot air balloon and by Problem Four were beginning to approach the Problems with this mindset. All groups recognized that they would need to make assumptions and simplifications to model the heat flow into the cool box and developed an appropriate model with little guidance.

9.2.4. PBL's impact on developing students understanding of thermal physics

It is difficult to directly assess the impact of PBL on students understanding of thermal physics, as we have no control group. As a result we cannot compare the development of students' understanding through PBL with development of their understanding of the same concepts through lecture. It was evident in tutorials and from students' reports that they had developed an understanding of the thermal physics concepts that they were applying to solve the Problems, (apart from Problem Four). However, it was also evident from students' responses to the final exam that knowledge transfer is limited and this needs to be addressed. One possible way to do this would be to have tutorials after each Problem in which students completed questions which were based on the concepts that they had covered in the Problem, but where in different contexts. If these questions required more thought than typical end of chapter exercises but were less demanding than PBL problems, students would be able to complete a number of them during one tutorial and still benefit from them. In this way students would still begin the learning process through solving a PBL Problem, but they would also gain the benefit of seeing the relevance of the concepts to different areas of physics. Although this may not significantly increase students' ability to transfer their knowledge, it should improve it, as they are being given opportunities to apply their knowledge in different contexts before a final examination.

9.2.5. Differences in the Science Education and Physics students' performance

As can be seen from the graph below in figure 9.1, the Science Education students (groups H, I and J) performed slightly better overall than the Physics students. One reason that could be attributed to this is that they have had more experience of group work and a longer period of time interacting with one another, as they are in the second year of their course. It was evident during PBL tutorials that the Science Education groups adjusted more readily to the new methodology; this may be a result of their experiencing a variety of teaching methodologies in their studies.

Figure 9.1 also shows that there was no significant difference between the Physics with

Astronomy (groups E, F and G) and Applied Physics students (groups, A, B, C and D). It is interesting to note that it wasn't the highest ability Applied Physics group that achieved the highest report grades. This was most likely a result of their ability to work well together as a group.

The difference between the groups' average continuous assessment and average exam marks was approximately 10% for each group, as shown in figure 9.1. The variation in these performances may be explained by the differences between the exam and PBL environment. During the exam, time constraints, stress, and lack of conferring with other students were the most likely reasons for achieving lower grades. The one group that received lower marks in the assessments than in the exam was experiencing difficulties with the group work aspect of the module.

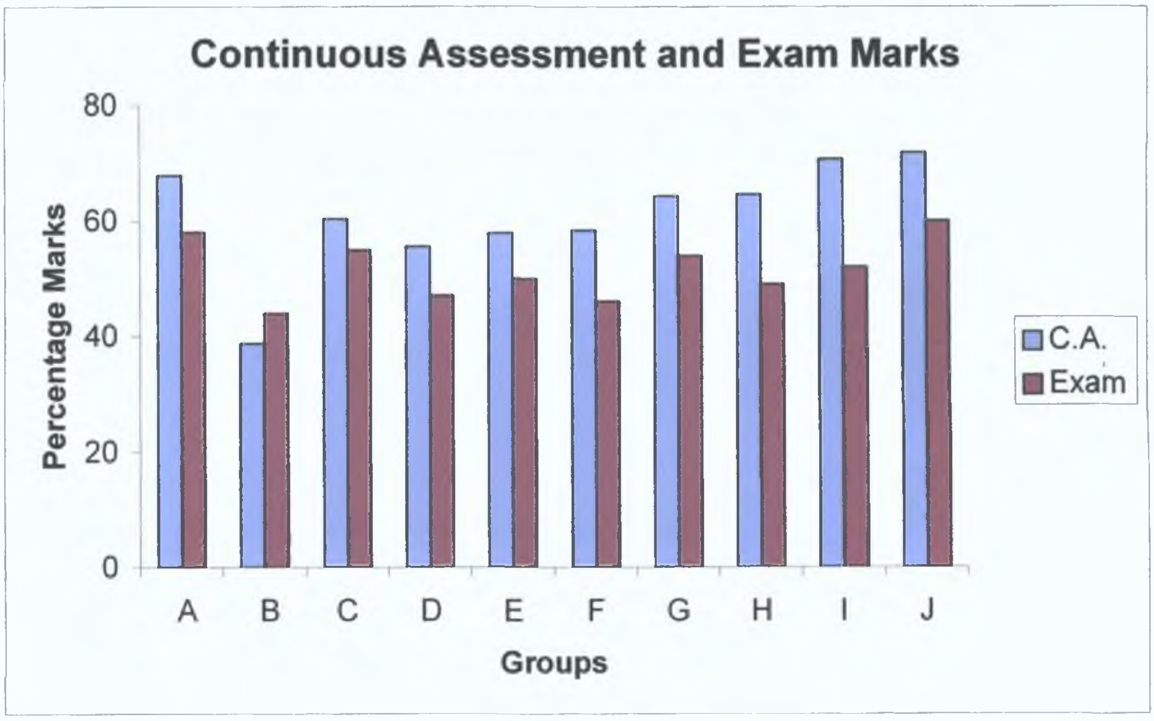

__Figure 9.1__ Graph showing groups' continuous assessment and final exam marks for the PBL thermal physics module.

9.3. Recommendations for improvement of the PBL module

9.3.1. Addition of other PBL modules

Overall the module was successful in accomplishing the aims and objectives that it was developed to achieve; however there are some improvements that could be made to increase its effectiveness. Firstly, it would be beneficial if there were other modules of the students courses delivered through PBL. Although only having one course delivered in this manner didn't lessen the benefits, having others given in the same way may increase these benefits greatly. It would be particularly useful to have students laboratories run through PBL. This would mean that in addition to gaining the benefits of the PBL methodology in two modules, students would also be looking at similar concepts in their labs and tutorials. Completing their labs thorough PBL would complement the PBL tutorials on the same topic. Students would be enabled to look at topics from different perspectives, solving different Problems using knowledge they had gained from either labs or tutorials. As well as PBL labs reiterating and emphasising topics that students are studying in PBL tutorials they may also increase students understanding of experimental procedures. The use of PBL to develop students' deep learning approaches would be very beneficial to a lab situation, as it would help to ensure that students really understood the experiment they were conducting rather than just looking for results. We saw some of the advantageous of using PBL for experimental work during Problem Six.

9.3.2. Providing computer facilities in the PBL classroom

The facilities provided for students during the PBL module were excellent. There was a dedicated room with arranged group seating. This meant that students had their own group space to work in each tutorial. The room was equipped with books, a screen and overhead projector. There were also computer facilities available in the next room for students to use. As students had to move from the group and into another room to research they had no one to discuss information or possible solutions with straight away. It also meant that facilitators were away from students as they were researching and so if they required guidance they would have to actively seek out a facilitator to speak with. In order to improve students work rate, having computers in the tutorial room would be very beneficial. This has been arranged and will be the case for the next delivery of the module.

9.3.3. Developing PBL groups formed from students from all three class groups

The reason that the PBL groups were not formed using a mixture of each class group was that we felt that it would be difficult for students to arrange a group meeting time outside lectures and tutorials. We still feel that this would prove very difficult, having group members from three different timetables. Organisation of group meetings was one element of the module that students noted to be very difficult and that was with all group members on the one timetable. Currently, with each class group having very different timetables the benefits of mixing groups would be outweighed with the difficulties in them functioning successfully.

However, if timetabling difficulties could be dealt with then it may be advantageous to create PBL groups using students from all three class groups. The differences in students' backgrounds and emphasis were very evident from their reports. Particularly in Introductory Problem and Problem Three, were students were asked something involving an educational element. The Science Education students concentrated on the educational merits of PBL and the methodology itself in answering the Introductory Problem, while the Physics students concentrated on how it would affect their skills for future employment. The Science Education students also brought more of an educational background to the demonstration in Problem Four. It may be beneficial to mix students from the education and physics disciplines in order to give them a more rounded viewpoint of PBL and also to enable to see different approaches to the physics that they are studying. There was also evidence that the Physics students tended to have a slightly more mathematical approach to solving questions as they had studied more mathematics and would be used to looking at topics in this way, whereas the Science Education students tended to approach Problems in a qualitative manner. Mixing groups of students would give them a range of viewpoints and methods of solving Problems and also present them with an opportunity to learn from one another.

9.3.4. Assessment of the group work aspect of PBL

Finally, it would be advantageous to have the final exam in a PBL format rather than having students sit down and answer an individual written assessment. If it were possible to have the final exam as a PBL problem, students could be assessed on their group work, research and other critical thinking skills that they have developed throughout the module. Having a final written assessment really only assess students' understanding and knowledge content. However, as half of the marks were awarded for the PBL reports themselves, the development of critical thinking skills was assessed. It would be useful to have another level of assessment within the module to take into account the group work aspect. Although students' group work skills are being assessed through the marking of their group reports, there is no direct group work skills assessment. This proved difficult to complete, as it is problematical trying to establish a group work mark when students are completing most of the group work outside the module. One possible solution would be to award a certain amount of marks from each report to students' group work alone, rather than only to the solution to the Problem.

9.4. Conclusion

The general aim of the PBL thermal physics module was to develop students' understanding of thermal physics while at the same time equipping them with critical thinking skills. We wanted the learning process to be student cantered and active. Our objectives included: students developing a deep rather than shallow understanding of the concepts they were studying, that they would develop their groupwork and research skills and are able to apply their knowledge to different situations. There is evidence, as outlined in this thesis of the development of students' understanding of thermal physics and groupwork and research skills. However, they were also difficulties with implementing PBL. There were some instances in which students understanding was not developed, for example students understanding of the Second Law of Thermodynamics and the Carnot cycle in Problem Four. There is also evidence that students still have difficulties in transferring the knowledge that they have acquired to new situations. Since this is an indicator of deep learning, we must conclude that our aims were not entirely met.

There were other concerns involved in the implementation PBL. For example, the large amount of staff time dedicated to the development and implementation of the module. Four staff members were required to deliver the thermal physics module through PBL to forty eight students, whereas one would have sufficed to deliver it through lecture. There were also problems in relation to the group work aspect of the module, with some students not participating as they should. Finally, there was less content involved in the module than there would be in a traditional lecture based one. However there were many benefits seen from the introduction of PBL, students and staff were more motivated, students group work and research skills improved and they developed a more in-depth understanding of the concepts they were studying. Overall the module achieved the learning outcomes and at the end of the module students' attitudes to PBL were overall positive, the majority felt that they had gained a lot from completing the module.

To determine if students retain the information for longer than they would with a lecture based course and to directly assess the difference between PBL students' understanding and lecture students' understanding of concepts taught further research would be necessary with a lecture control group. This would also provide an opportunity to research into the extent to which PBL increases students' ability to transfer what they have learned to new situations.

The PBL module developed students understanding of thermal physics concepts and their critical thinking skills, although it failed in developing their ability to transfer knowledge. With further modifications however, the PBL module should become improved at achieving this objective. In conclusion, if we want to produce students who are capable of lifelong learning, solving problems, completing research and who have a deep understanding of subject material then PBL is a methodology that can be used to achieve this.

Appendix A: Problems and corresponding assessment matrices

Matrix of educational aims the Problems were developed to achieve:

Objective	**Intro Prob**	**Prob 1**	**Prob 2**	**Prob 3**	**Prob 4**	**Prob 5**	**Prob 6**
Understand basic thermal physics concepts.		X	X	X	X	X	X
Correctly apply and use all formulae covered in the learning outcomes of the problems.		X		X		X	X
Manipulate formulae and relate equations.		X		X		X	X
Graph data correctly and use their graphs in order to analyse data.							X
Use spreadsheets effectively.							X
Instinctively use graphing as a method of determining the relationship between variables.		X		X			X
Estimate order of magnitude of their answers.		X				X	
Work successfully as part of a team.	X	X	X	X	X	X	X
Effectively research topics and retrieve information.	X	X	X	X	X	X	X
Apply their previous knowledge in solving new problems.	X	X	X	X	X	X	X
Communicate well with other members of the group and tutors.	X	X	X	X	X	X	X
Develop peer-mentoring skills through explaining aspects of physics to others in their group.	X	X	X	X	X	X	X
Develop life long and self-directed learning skills through working through the problems.	X	X	X	X	X	X	X
Recognise the link between physics and other disciplines.		X	X			X	
Appreciate the value of what they are learning and its appropriateness to their future careers as scientists.	X	X	X	X	X	X	X
Understand the importance of carrying out practical work in science.				X			X
Carry out experimental procedures safely and correctly.				X			X

Introductory problem

During your teaching practice you discover that it just seems impossible to make certain lessons interesting to your students. You decide that it's time to try some other method, and think that perhaps things would be better if the students got actively involved in the teaching process.

Part 1

You read up on the subject and get particularly interested in the area of Problem Based Learning in small groups. After a lot of humming and hawing you decide to give PBL a real go. How would you go about convincing your students that PBL can be a much more exciting way of learning science? What difficulties do you anticipate and how would you try to avoid these?

Part 2

You feel that assessing the groups is a potential minefield. For example, you don't want one person to dominate the group (either by dominating the discussions or by doing all the work) nor do you want any hangers-on (either by not participating fully or being continually late). What is your strategy to prevent this and what role can assessment play in this?

Assessment: Prepare a 10 minute talk in which you present your ideas.

Assessment matrix for the Introductory Problem

What is PBL?

Comments	A	B	C	D	E	F	G	H	I	J
Both curriculum and process		X								
Involves role changes		X	X							
Is self-directed learning		X	X							
The problem drives learning			X	X	X		X	X	X	
Students work in groups	X		X		X		X	X		X
Good for mixed ability								X		
Problems are real world based						X	X		X	
Is a form of student centred learning				X	X	X				
Problems are ill structured						X				
No definite right answer						X				
Is interdisciplinary						X				

Advantages of PBL:

Comment	A	B	C	D	E	F	G	H	I	J
Student centred		X	X					X	X	
Students are active rather than passive						X				
Own goals rather than instructors		X						X	X	
Learning by overcoming difficulties		X								
Solving the problem drives the learning		X					X			
Feedback is immediate		X								
Change from usual methodologies	X							X	X	X
Better motivation	X		X		X		X	X		
Better retention of knowledge				X				X		
Improves critical thinking skills						X	X	X		X
Improves problem solving skills						X	X	X		
Improves group work skills	X			X		X	X	X	X	X
Good for mixed abilities				X				X	X	
Good preparation for employment	X				X		X			
Results in better understanding										X
Instils life-long learning skills				X						

Disadvantages of PBL

Comments	A	B	C	D	E	F	G	H	I	J
Lack of student participation in the group	X	X	X	X	X		X	X	X	X
Differences of opinion between group members	X	X	X		X		X			X
Student not using time efficiently										X
May not be suitable to use with practical work										X
Time restrictions									X	X
Problems with different levels of ability	X	X	X		X			X		
Domination of group by one member	X	X	X		X		X	X	X	
Division of tasks resulting in less learning	X									
Conflicting personalities	X	X	X	X	X		X			
Lack of resources									X	
Student goals mismatched with instructors				X				X	X	
Student concerns over change and grading							X			
Problems with coordinating group meetings		X					X			
Problems with lack of motivation			X							

Strategies to overcome difficulties:

Comments	A	B	C	D	E	F	G	H	I	J
Be aware of possible group problems and discuss	X	X	X							
Ensure all members are comfortable to speak		X								
Support and encourage group members	X	X								
Encourage respect and compromise	X	X	X							
Make attendance compulsory			X	X			X	X	X	
Mark attendance			X	X			X	X	X	
Award group and individual marks				X			X		X	X
Only award group mark					X					
Only award individual mark								X		
Have continuous assessment assignments			X							
Assign roles and rotate them				X						X
Monitor progress by observation and questioning	X								X	X
Divide task up amongst group members	X		X		X		X		X	
Ensure resources readily available							X			
Provide clear learning outcomes					X					

Thermal Physics – Problem One

Part 1

Bob and Martha are physicists who live in a house that was built in the 1960s. The house has a central heating system and is generally in good condition, but there is no form of insulation in the house.

On a cold winter's day, the heating system breaks down suddenly. While they're waiting for the plumbers to arrive, they monitor the temperature in the living room. What factors determine how quickly the temperature will decrease?

Part 2

With the heating system no longer functional the temperature in the house is dropping substantially, Bob notes that it has dropped by 4^0C after the first hour and he is getting worried about his goldfish. On the one hand he doesn't want to leave Martha on her own in the house, on the other hand he knows once it gets too cold the goldfish will probably die. How long does he have before he has to leave the house to save the goldfish?

Part 3

The plumbers arrive in time and get the heating system going in no time. With his goldfish swimming happily in their bowl, Bob and Martha now realise that this episode has given them a good if unwanted opportunity to see if insulating the house is economically viable. After estimating the surface area of their house they estimate its overall thermal transmittance.

To see what kind of insulation they need most, they consider two options: insulating the walls and roof with Styrofoam or replacing the windows with double-glazing. After a bit of research they collect some data that is tabulated on the next page.

They probably don't have enough money in the bank to pursue both options at once. Through a friend they know that can get either at roughly the same price. Their decision will therefore be based on how much they save on the heating bill. Which option should they go for?

Material	**U (Wm^{-2}°C^{-1})**
Styrofoam	0.25
Double glazing	1.4
Single glazing	3.4
Roof	1.8
Walls	2.3
Outer wall/roof surface	8.3
Inner wall/roof surface	17

Note: The outer wall and inner wall transmittances arise because a surface layer of air builds up that attains a temperature different from the ambient indoor or outdoor temperature.

Part 4

There is a grandfather clock in the living room of the house. After a couple of weeks they notice that the clock is running slow. Bob and Martha suspect this is because the room is hotter than before they insulated the house. Carry out calculations to check if this is a likely cause.

Could the pendulum be used as a thermometer?

Assessment: Write a report outlining how you solved the problem

Assessment matrix for Problem One

Part 1: Factors affecting heat loss

Criteria	A	B	C	D	E	F	G	H	I	J
Formulae excluded	X	X	X		X	X	X	X	X	
Considered conduction, convection and radiation	X	X	X		X	X	X	X	X	X
Mentioned dependence on difference between inside and outside temperature	X			X	X	X	X			X

Part 2: Newton's law of cooling

Criteria	A	B	C	D	E	F	G	H	I	J
Justify use of Newton's Law of Cooling (NLC)	X							X		
Extract value from formula										
State assumptions:										
Conduction, convection, radiation or combination?					X					
Constant outside temperature						X				
No heat sources in the house		X	X							
Fish bowl cools at same rate as house	X		X	X	X	X				
No confusion between different forms of NLC	X	X	X			X	X	X	X	
Gave reference for goldfish death temperature	X			X				X		
Graph:										
Units	X			X			X	X		X
Captions							X			
Line or dots					X					
Asymptote (final value)	X	X			X					
Link heat loss with NLC	X							X	X	
Formula relating heat to temperature change inside house								X		
Formula relating heat flow rate to temperature difference between inside and outside					X			X		X

Part 3: Insulation

Criteria	A	B	C	D	E	F	G	H	I	J
Estimation of area of the house	X		X	X	X	X	X	X	X	X
Definition of U value	X		X					X		X
Definition of R value										
Reason why you can add R values but not U										X
Relationship between R and U values	X		X			X	X	X	X	
Formula for determining U values	X					X	X			X
Calculations of U values for insulated house with single glazing and non insulted house with double glazing	X		X	X		X	X	X	X	X
Relationship between total heat transmitted, U value, area and difference in temperature	X		X	X		X		X	X	X
Calculation of total heat transmitted in both cases	X		X	X	X	X	X	X	X	X
Conclusion regarding which option to go for	X		X	X	X	X	X		X	X

Part 4: Thermal expansion

Criteria	A	B	C	D	E	F	G	H	I	J
State assumptions:										
Increase in temperature of the house.	X	X	X	X	X	X	X	X	X	X
Material of the pendulum	X	X	X	X	X	X	X	X	X	X
Estimation of the original length of the pendulum	X	X	X	X	X	X	X	X	X	X
Relationship between increase in length and period of the pendulum	X		X	X	X	X	X	X	X	X
Calculation of original period and period after heating	X	X	X		X	X	X	X	X	X
Estimation of the amount of time the clock will run slow due to increase in temperature	X		X		X	X	X			
Explanation of thermal expansion						X				
Use of thermal expansion formula and explanation of variables in it.	X	X	X	X	X	X	X	X	X	X
Justification of answer regarding whether or not the clock could be used as a thermometer	X		X	X	X		X	X	X	X

General

Criteria	A	B	C	D	E	F	G	H	I	J
Numbered equations			X						X	
Have captions										
State units	X		X	X	X	X			X	X
Significant figures										
Isolate variables first										
Show evidence of research	X		X	X		X	X	X	X	
Justify use of equations	X							X		
State and justify assumptions and methods used										
Have appropriate types of graph										

Results

Marks	A	B	C	D	E	F	G	H	I	J
Part 1	9	6	9	5	6	8	7	7	7	8
Part 2	25	19	22	12	17	20	17	25	21	15
Part 3	29	0	29	17	10	27	22	19	21	27
Part 4	14	10	16	10	15	13	14	13	12	13
Total	77	35	76	44	48	68	60	64	61	63

Thermal Physics – Problem Two

Part 1

You are doing some research in the library and you come across an article on Steve Fossett's solo circumnavigation of the world in a hot air balloon. You think that this was an amazing achievement and become really interested in hot air ballooning. After some investigation into the topic you decide to build your own hot air balloon. You start off with modelling a simple airship: essentially a basket underneath a balloon (called "the envelope") made of 1 mm thick mylar. Why is mylar a good choice of material? What factors determine the volume of the balloon that you need to float at a given height?

Part 2

You decide that you would like to float at a height of about 2 km. You use a propane burner to heat the air inside the balloon, but for safety reasons you don't want to exceed a temperature of 150°C. Estimate the minimum number of square metres of material you need to do this if the bottom of the balloon is open.

Part 3

Determine the heat loss per hour from the balloon in flight.

Assessment: Write a newspaper article about the building of your balloon.

Assessment matrix for Problem Two

Part 1: Factors affecting volume of the balloon

Criteria	A	B	C	D	E	F	G	H	I	J
Formulae excluded	X	X	X	X	X	X	X	X	X	X
Mentioned why Mylar was a good material to use in a hot air balloon.	X	X	X	X	X	X	X	X	X	X
Listed at least five factors			X	X				X	X	

Part 2: Determining the surface area required to float at 2km height

Criteria	A	B	C	D	E	F	G	H	I	J
Understand that buoyant force must equal the weight of the balloon and basket in order for it to float.	X	X	X	X	X	X	X	X	X	X
Be able to relate Archimedes' principle to the balloon.	X	X	X	X	X	X	X	X	X	X
Understand that the mass of air inside the balloon is important.	X		X	X		X	X	X	X	X
Relate the mass of gas to its density and volume	X	X		X	X	X	X	X	X	X
Extract the formula for the volume of the balloon from the equation written using Archimedes' principle.	X	X	X	X	X		X	X	X	X
Justify the use of the Ideal Gas Law							X		X	
Manipulate the IGL in order to obtain an expression for density.	X				X		X	X	X	X
Calculate the density of the hot and cold air.	X			X	X		X	X	X	X
Calculate / State the pressure at 2 km	X	X		X	X	X	X	X	X	X
Calculate / State the temperature at 2 km	X	X		X	X	X	X	X	X	X
Calculate the volume of the balloon	X	X	X	X	X	X	X	X	X	X
Calculate the surface area of the balloon	X	X	X	X	X	X	X	X	X	X
State any assumptions	X	X	X	X	X			X	X	X

Part 3: Estimating heat loss from the balloon.

Criteria	A	B	C	D	E	F	G	H	I	J
Used k value	X	X	X	X	X		X			
Used R or U value						X				
Checked to see if their answer was reasonable		X		X	X				X	X
Estimated heat into the balloon and from this the amount of heat lost per hour.								X	X	X
Used another suitable method.										
Stated any assumptions.	X				X	X			X	

Newspaper article:

Criteria	A	B	C	D	E	F	G	H	I	J
Content:										
Explain in detail all parts of the problem	X	X		X	X		X	X	X	
Interesting and newspaper like	X		X	X		X	X	X	X	
Presentation:										
Well laid out	X	X	X	X	X	X	X	X	X	
Presented like a newspaper article			X	X	X	X	X	X	X	

General:

Criteria	A	B	C	D	E	F	G	H	I	J
Numbered equations						X	X	X	X	X
Have captions	X				X		X			X
State units	X		X	X	X		X	X	X	X
Correct significant figures			X							
Isolate variables first	X	X	X	X	X		X	X	X	X
Show evidence of research	X		X	X	X		X	X	X	X
Justify use of equations									X	
State and justify assumptions and methods used	X								X	X

Results:

Marks	A	B	C	D	E	F	G	H	I	J
Part 1	8	6	7	6	7	7	6	7	8	7
Part 2	34	20	20	26	30	25	33	34	37	35
Part 3	9	8	8	9	10	8	8	11	15	17
Article	22	17	25	25	20	25	22	26	25	18
Total	73	51	60	67	67	65	69	78	85	77

Thermal Physics – Problem Three

Part 1

You are preparing a classroom demonstration to show your students some of the effects of heating a gas. The following equipment is available to you in the lab: a calorimeter, a Pyrex test tube equipped with a lightweight plastic piston, a thermocouple, a stopper, a Bunsen burner, clamps and retort stands.

The first stage of your experiment is designed to show the effects of adding heat to a gas at constant pressure. Sketch a simple experimental set-up that will allow you to demonstrate this to your class. Make sure that effects will be clearly noticeable.

Part 2

The second stage of your experiment is designed to show the effects of adding heat to a gas at constant volume. Sketch a simple experimental set-up that will allow you to demonstrate this to your class. Indicate how your students can work out the temperature and pressure in the test tube after your experiment.

Part 3

In the third stage of your experiment you wish to demonstrate isothermal processes as well as the difference between process variables and state variables. Describe a simple experiment that will allow you to demonstrate this to your class, e.g. using the test tube you've prepared in part 2.

Part 4

A common error made by your students is the assumption that if the temperature of a system changes, some heat transfer must have occurred. Design an experiment to rectify this misconception.

Part 5

After the demonstration, you decide to ask your students a thermodynamics question as part of their homework. You give them initial and final states for the system, along with the change in internal energy. Can they work out whether the energy change was due to the applied heat or the work done on the system? Discuss this in relation to the first law of thermodynamics.

Assessment: Write a report outlining how you solved the problem

Assessment matrix for Problem Three

Part 1: Heating gas at constant pressure

Criteria	A	B	C	D	E	F	G	H	I	J
Correctly explaining what happens when an ideal gas is heated at constant volume	X	X	X	X	X	X	X	X	X	X
If they assume that the number of moles is constant that they state this				X			X		X	X
Understanding that the volume is constant throughout the process	X	X	X	X	X		X	X	X	X
Valid method of demonstrating the process	X	X	X	X	X		X		X	X
Clear labelled diagram	X	X	X	X	X	X	X	X	X	X
Explanation of how temperature and pressure may be worked out after the demonstration is complete			X		X	X	X	X	X	X
Understand volume is not the same as amount of gas		--	X		X	--	X	X	X	X

Part 2: Heating gas at constant volume

Criteria	A	B	C	D	E	F	G	H	I	J
Justifying the use of the Ideal Gas Law										
Correctly explaining what happens when an ideal gas is heated at constant pressure	X	X	X	X	X	X	X	X	X	X
If they assume that the number of moles is constant that they state this										
Understanding that the pressure is constant throughout the process	X	X	X	X	X	X	X	X	X	X
Explanation of why pressure is constant		X								
Valid method of demonstrating the process	X	X	X	X	X	X	X	X	X	X
Clear labelled diagram	X	X	X	X	X	X	X	X	X	X
Show effects are clearly visible										

Part 3: Isothermal processes

Criteria	A	B	C	D	E	F	G	H	I	J
Explanation of what an isothermal process is	X	X	X	X	X	X	X	X	X	X
Show understanding of how isothermal processes are related to the first law of thermodynamics			X	X		X	X	X	X	X
Valid method of demonstrating an isothermal process	X						X		X	X
Correct explanation of what state and process variables are				X				X	X	X

Part 4: Adiabatic processes:

Criteria	A	B	C	D	E	F	G	H	I	J
Explanation of what an adiabatic process is	X	X			X	X	X	X	X	X
Understanding of how the first law of thermodynamics can be applied to adiabatic processes					X		X		X	X
Valid method of demonstrating an adiabatic process	X	X	X	X	X	X	X		X	X

Part 5: State and process variables:

Criteria	A	B	C	D	E	F	G	H	I	J
Show understanding of process and state variables	X									X
Correct answer to question	X			X	X		X	X	X	X
Explanation of how state and process variables are related to the first law of thermodynamics	X			X	X			X	X	X
Understanding that process variables are path dependent whereas state variables are not									X	X

General:

Criteria	A	B	C	D	E	F	G	H	I	J
Numbered equations	X						X	X	X	X
Have captions	X		X	X		X		X		X
State units		X							X	
Correct significant figures										
Isolate variables first		X		X					X	
Show evidence of research	X			X	X	X			X	X
Justify use of equations		X	X				X			X
State and justify assumptions and methods used										

Results:

Marks	A	B	C	D	E	F	G	H	I	J
Part 1	13	15	12	13	12	13	13	13	13	13
Part 2	16	13	16	19	15	11	15	12	16	19
Part 3	13	11	14	15	8	10	10	15	14	19
Part 4	15	12	10	10	17	13	19	12	14	18
Part 5	15	7	9	15	15	10	15	16	16	17
Total	73	58	61	72	67	57	72	68	73	86

Thermal Physics – Problem Four

Part 1

Bob and some of his friends are going on a fishing trip on the South coast. They are going for 3 days, so they want to bring a cool box in which to keep what they catch. Decide on the volume of the cool box and estimate how much ice you would need to fill it with to keep the otherwise empty cool box at 0°C for this time.

Part 2

On somebody else's boat, Bob and his friends have noticed a cooler unit placed on top of a cool box. The cooling unit doesn't run too hot: it's warm to the touch, but doesn't burn the skin.

They consider buying such a system and find that the price wouldn't be prohibitive. Bob's friends worry about the energy consumption and ask Bob to work out how much energy would be drained from the boat's batteries.

Bob does some research and finds out from the manufacturer that the cooling unit runs at 43% of the theoretically attainable coefficient of performance at these temperatures. In order to find out how much energy would be drawn from the batteries, Bob estimates how much heat enters the empty cool box from the outside and from that works out how much energy needs to be drawn from the batteries.

Try and repeat Bob's calculations. Why is it best to place the cooling unit on the top of the box?

Part 3

Bob reckons optimistically that they will be able to catch 70 kg of fish. They store the fish in the cool box so they can bring it home to eat. They want to keep the fish frozen. How much energy needs to be drawn from the batteries in this case?

Assessment: Write a report outlining how you solved the problem

Assessment matrix for Problem Four

Part 1: Latent heat (Amount of ice needed)

Criteria	A	B	C	D	E	F	G	H	I	J
State assumption that most heat transfer through conduction	X		X	X		X	X	X	X	
State assumption of average constant outside temperature	X		X			X			X	
State assumption of constant temperature of 0^0C inside the cool box	X				X	X	X	X	X	X
State assumption that ice is at 0^0C when placed inside the cool box										
Use U values rather than k	X		X	X	X	X		X	X	X
Calculate the heat flow into the box over the three days	X	X	X	X	X		X	X	X	X
Explain what latent heat is / about changes of state			X	X		X	X		X	

Part 2: Carnot cycle (Energy drawn from batteries)

Criteria	A	B	C	D	E	F	G	H	I	J
Recognise that the heat into the cool box is equal to the heat that must be removed	X	X	X		X	X	X	X	X	X
State that most heat flow is through conduction	X		X	X		X	X		X	
Use U values rather than k	X	X				X		X	X	X
State that the top of the cool box is in thermal equilibrium with the bottom of the cooling unit		X								X
State that the temperature difference between the outside and inside of the cool box is the same on all other five sides		X		X		X	X	X	X	
Calculate the heat flow into the cool box	X	X		X	X	X	X	X	X	X
Calculate the CP ideal at these temperatures			X	X		X	X	X	X	X
Calculate the actual CP at these temperatures			X	X		X	X	X	X	X
Determine the work done by the cooling unit		X	X	X	X		X	X	X	X
Show an understanding of the Carnot cycle						X	X	X		X
Show an understanding of the 2nd Law of thermodynamics				X			X	X		X

Part 3: Specific heat capacity, latent heat and thermal conductivity (Energy drawn from batteries to keep fish frozen)

Criteria	A	B	C	D	E	F	G	H	I	J
Calculate heat removed in cooling the fish from original temperature to required temperature	X	X		X	X		X	X	X	X
Explanation of why they can use Q=mcΔT						X				X
Calculate amount of heat removed in freezing the fish	X	X		X	X		X	X	X	X
State that most heat flow is through conduction	X			X		X				
Calculate heat flow into the cool box over the length of time for the journey home			X	X	X	X				X
Calculate the CP at these temperatures									X	
Determine the work done by the cooling unit		X	X				X		X	X

General:

Criteria	A	B	C	D	E	F	G	H	I	J
Numbered equations	X	X	X			X	X	X	X	X
Have captions		X			X	X	X	X	X	X
State units	X	X	X	X	X	X	X	X	X	X
Correct significant figures				X						
Isolate variables first	X		X	X		X	X	X	X	X
Show evidence of research	X		X		X	X	X	X	X	X
Justify use of equations	X			X						
State and justify assumptions			X	X	X	X	X	X	X	X

Results:

Marks	A	B	C	D	E	F	G	H	I	J
Part 1 (20)	15	10	16	14	11	16	13	14	13	15
Part 2 (40)	16	20	23	30	22	25	33	35	27	35
Part 3 (30)	13	13	13	21	14	14	21	15	23	24
Presentation (10)	7	5	7	7	6	8	8	8	8	8
Total	51	48	59	72	53	63	75	72	71	82

Thermal Physics – Problem Five

Part 1

You are an astronomer studying the Interstellar Medium (ISM). You know that the ISM is gas, that it is mostly made of hydrogen and that it tends to clump in clouds. You have observed a hydrogen cloud in a HI region of space. You want to calculate the pressure inside the cloud in order to determine if it is likely to collapse and form a star. List any assumptions that you need to make about the particles of the cloud and calculate the pressure.

Part 2

Mapping of the cloud using a radio telescope shows emission corresponding to a wavelength of 21.11cm. This indicates to you that the cloud is composed of atomic hydrogen. However, you are wondering if atomic collisions may lead to the formation of molecular hydrogen in the cloud. Carry out calculations to see if this is likely.

Part 3

You have discovered another cloud; the only difference is that it is 10K hotter. What affect will this have on the pressure, density and likeliness of forming molecular hydrogen?

Assessment: Write a report outlining how you solved the problem

Assessment matrix for the Problem Five

Part 1: Kinetic theory assumptions

Criteria	A	B	C	D	E	F	G	H	I	J
Assumptions:										
All particles are identical										X
Particles are in motion and obey Newton's Laws	X								X	X
Particles are small in comparison to distance between them (no particle-particle interactions)	X								X	X
Collisions between particles and "container" are elastic	X							X	X	
Show understanding of kinetic theory										
Explain why they can use the IGL	X				X			X	X	X
Estimate realistic temperature, and density	X	X	X	X	X	X	X	X	X	X
Calculate volume	X		X	X	X	X	X	X	X	X
Calculate no. of particles / no. of moles	X		X	X	X	X	X	X	X	X
Determine if it will form a star (not required)	X	X		X		X	X		X	

Part 2: Mean free time

Criteria	A	B	C	D	E	F	G	H	I	J
Show an understanding that the particle collisions depend on the distance between atoms, and speed and size of the atoms.	X		X		X				X	
Show an understanding of root mean square speed			X						X	
Show an understanding of mean free path									X	
Show an understanding of mean free time										
Calculate the root mean square speed	X		X	X	X	X	X	X	X	X
Calculate the mean free path	X			X	X			X	X	X
Calculate the mean free time		X		X	X	X	X	X	X	X
Explain why collisions are / aren't likely	X	X	X	X	X	X	X	X	X	X
Calculate the collision frequency				X	X					

Part 3: Effect of temperature on pressure, density and collisions

Criteria	A	B	C	D	E	F	G	H	I	J
State any assumptions, such as the cloud is in pressure equilibrium with its surroundings or it is at constant volume	X		X		X		X	X	X	X
Show an understanding of how the decrease in temperature will affect pressure	X		X		X		X		X	X
Show an understanding of how the decrease in temperature will affect density	X		X		X		X		X	X
Show an understanding of how the decrease in temperature will affect collision rate	X				X	X	X	X	X	X
Carry out calculations to support their answers	X	X	X			X		X	X	X

General:

Criteria	A	B	C	D	E	F	G	H	I	J
Numbered equations		X	X		X	X	X	X	X	X
Have captions	X	NA	NA	NA	X	X	X	NA	NA	NA
State units	X	X	X	X	X	X	X	X	X	X
Correct significant figures	X								X	
Isolate variables first		X	X	X	X	X	X	X	X	X
Show evidence of research	X			X	X	X	X	X	X	X
Justify use of equations			X						X	
State and justify assumptions	X			X	X					X

Results:

Marks	A	B	C	D	E	F	G	H	I	J
Part 1 (35)	25	16	18	18	22	15	16	19	27	22
Part 2 (30)	20	14	14	20	24		19	19	23	19
Part 3 (25)	18	10	15		18	12	13	14	19	18
Presentation (10)	7	6	7	7	8	7	7	7	9	8
Total	70	46	54	45	72	34	55	59	78	67

Thermal Physics – Problem Six

Part 1

You are working in the research and development department of an insulation manufacturer. The current products that the company produce are successful in preventing heat transfer through conduction and convection, but not very effective at preventing heat transfer through radiation. You have been assigned the task of adapting one of the products in order to make it capable of preventing heat transfer by all methods. What factors will you need to consider when choosing the material / materials for your insulation?

Part 2

After careful consideration you decide that coating the original form of insulation in a thin layer of metal to reflect radiant heat would be the best option. You've chosen aluminium foil for your material, as it is light, strong, malleable, impermeable to moisture and light, safe and cost effective. You want to investigate the heating and cooling of unmodified aluminium and aluminium that has been painted matt black in order to determine which would be better at reducing heat transfer by radiation. Develop and carry out an experiment that will enable you to study the heating and cooling of the two types of aluminium.

Part 3

Now that you have heating and cooling data for silvered and blackened aluminium you need to analyse it in order to determine which should be used as the insulation material. Develop a mathematical model to approximate the heating and cooling of the foil and use it to curve fit your data. Determine the ratio of emissivities of Aluminium and black paint.

Assessment: Write a report outlining how you solved the problem

Assessment matrix for the Problem Six

Part 1: Factors affecting choice of insulation material

Criteria	A	B	C	D	E	F	G	H	I	J
Didn't include formulas			X	X		X	X	X		X
Mentioned factors not related to the material such as cost and location			X			X			X	X
Mentioned factors relating to the material itself such as emmisitvity and U value	X		X	X		X	X	X	X	X
Listed at least six factors to be considered			X						X	X

Part 2: Experimental design and results

Criteria	A	B	C	D	E	F	G	H	I	J
Listed reasons why aluminium is suitable	X		X	X	X	X	X	X	X	X
Draw diagram of the experimental set up	X			X	X	X	X	X		X
Explain method	X		X	X	X	X	X	X	X	X
Explain why they chose the set up they did	X		X	X				X		
Thought about how they could minimise conduction and convection and examine just radiation			X							
Show evidence of keeping conditions constant for black and silver, example turning the lamp on for a constant amount of time before taking data			X	X	X	X		X	X	X
Removed heat source before taking cooling data	X		X			X	X	X		X
Show evidence that they tried to minimise errors	X			X				X		
Picked a reasonable time interval between data points	X		X		X	X	X	X	X	
Produced reasonable graphs for heating					X					
Produced reasonable graphs for cooling									X	
Produced reasonable graphs for heating and cooling	X		X			X	X	X		X
Suggest reasons for any inconsistencies in their graphs	X			X						X

Part 3: Analysing data

Criteria	A	B	C	D	E	F	G	H	I	J
Attempted to use the Stephan-Boltzmann equation to develop an expression for the heating / cooling of the foil	X		X		X		X	X	X	X
Plot rate of change of temperature V's temperature difference			X					X	X	X
Obtain the constant for black and silver foil									X	
Determine the ratio of emissivities									X	

General:

Criteria	A	B	C	D	E	F	G	H	I	J
Numbered equations			X			X		X	X	X
Have captions						X				X
State units	X		X	X		X	X	X	X	X
Correct significant figures	X		X	NA	NA	X	X	X	X	X
Isolate variables first	X		X	NA	NA	X	X	X	X	X
Show evidence of research						X		X	X	X
Justify use of equations								X		
State and justify assumptions	X		X	X	X	X	X	X	X	X

Results:

Marks	A	B	C	D	E	F	G	H	I	J
Part 1 (10)	5		7	7	0	8	6	6	7	8
Part 2 (50)	40		33	35	29	35	39	40	28	38
Part 3 (30)	12		18	0	12	12	12	20	22	18
Presentation (10)	6		7	6	5	9	6	9	8	9
Total	63	0	64	46	46	64	63	75	65	73