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Physics Students' Approaches to Learning and Cognitive Processes in Solving Physics Problems

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ABSTRACT

This study examined traditional instruction and problem-based learning (PBL) approaches to teaching and the extent to which they foster the development of desirable cognitive processes, including metacognition, critical thinking, physical intuition, and problem solving among undergraduate physics students. The study also examined students' approaches to learning and their perceived role as physics students. The research took place in the context of advanced courses of electromagnetism at a Canadian research university. The cognitive science, expertise, physics and science education, instructional psychology, and discourse processes literature provided the framework and background to conceptualize and structure this study. A within-stage mixed-model design was used and a number of instruments, including a survey, observation grids, and problem sets were developed specifically for this study. A special one-week long problem-based learning (PBL) intervention was also designed. Interviews with the instructors participating in the study provided complementary data.

Findings include evidence that students in general engage in metacognitive processes in the organization of their personal study time. However, this potential, including the development of other cognitive processes, might not be stimulated as much as it could in the traditional lecture instructional context. The PBL approach was deemed as more empowering for the students. An unexpected finding came from the realisation that a simple exposure to a structured exercise of problem-solving (pre-test) was sufficient to produce superior planning and solving strategies on a second exposure (post-test) even for the students who had not been exposed to any special treatment. Maturation was ruled out as a potential threat to the validity of this finding. Another promising finding appears to be that the problem-based learning (PBL) intervention tends to foster the development of cognitive competencies, particularly physical intuition, even if it was only implemented for a short period of time. Other findings relate to the nature of the cognitive actions and activities that the students engage in when learning to solve electromagnetism problems in a PBL environment for the first time and the tutoring actions that guide students in this context.

RÉSUMÉ

Cette étude s'est intéressée à l'enseignement magistral ainsi qu'à l'apprentissage par problème (APP) dans le cadre des cours d'électromagnétisme avancé de niveau baccalauréat. Plus précisément, la recherche s'est penchée sur le potentiel respectif de ces deux approches de l'enseignement pour le développement de processus cognitifs souhaitables tels que la métacognition, la pensée critique, l'intuition physique ainsi que les habiletés de résolution de problèmes chez les étudiants de physique. L'étude portait également sur les approches de l'apprentissage des participants ainsi que sur leurs perceptions de leur rôle comme étudiants de physique. Cette étude s'est déroulée dans une université canadienne axée sur la recherche. Les écrits émanant des domaines des sciences cognitives, de l'expertise, de l'enseignement de la physique et des sciences, de la psychologie instructionelle, de même que des recherches sur les mécanismes langagiers ont fourni les cadres conceptuels qui ont permis d'élaborer et de structurer la recherche. Une approche méthodologique mixte a été adoptée dans le cadre de cette étude. Différents instruments, incluant un questionnaire, des grilles d'observations ainsi que des problèmes d'électromagnétisme ont été développés spécifiquement pour cette recherche. De plus, une intervention spéciale d'APP d'une durée d'une semaine a été mise en place. Des données complémentaires ont été recueillies par l'intermédiaire d'interviews avec les enseignants qui ont collaboré à la recherche.

Les résultats de l'étude suggèrent que, de façon générale, les étudiants utilisent des stratégies métacognitives lors de leurs périodes personnelles d'études. Toutefois, il semble que ce potentiel, ainsi que le développement d'autres habiletés cognitives, ne soient pas suffisamment stimulés dans le cadre des cours magistraux de physique. En ce sens, l'APP s'est avéré particulièrement prometteur. De façon surprenante, il semble qu'une seule exposition à des exercices structurés de résolution de problèmes lors du pré-test ait suffit à produire des résultats supérieurs en termes de qualité de la planification et de la solution des problèmes lors du post-test, et ce, même chez les participants qui n'avaient pas été exposés à aucun traitement spécial. La maturation a pu être écartée comme cause possible de biais dans l'observation de ce résultat. Un autre résultat particulièrement prometteur se situe dans le fait que l'APP tend à favoriser le développement de compétences cognitives, particulièrement l'intuition physique, même si l'intervention n'a été que de courte durée. D'autres résultats portent sur les actions cognitives et sur les activités dans lesquelles les étudiants s'engagent lorsqu'ils abordent la résolution de problèmes d'électromagnétisme dans un contexte d'APP pour la toute première fois. Les interventions pédagogiques du tuteur dans ce même contexte ont également été investiguées.

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CHAPTER 1 – INTRODUCTION

"[T]he most valuable asset of any society in the coming decades is a knowledgeable, thinking citizenry – human capital is the wisest investment" (Halpern, 1998). Employers now expect university graduates to display a range of capacities that go beyond content knowledge (Dickie, 2003) and include complex cognitive abilities such as problem-solving abilities as well as interpersonal skills required for team work (Blake, 1995). This is particularly the case with graduates of science programs since society in general has great expectations for scientists. We count on them to lead in many domains such as technology and communication research, software development, medical research, and these fields are linked to cognitively demanding professions.

The aspirations are the same for students in science programs: they are expected to become good citizens and be able to use their cognitive abilities in everyday life as mature and independent adult learners. To improve the quality of student thinking "means to raise it to a level of performance in academic contexts as well as civic and personal life that consistently exhibits the characteristics of high-quality thinking" (Beyer, 1997, p. 4). This is a challenging mission for universities. There is a tendency, particularly in science programs, to assume that students should come to university with the appropriate "tool box" of cognitive and reasoning skills to be successful. In a study conducted in Maryland, Miller & Morgan (1997) came to the conclusion that the community college and university English and mathematics faculty members believed that college-level course work is designed for mature learners who take responsibility for their learning. "Problem-solving utilizing higher-order thinking" was found to be the first and most important category among the defining characteristic of college-level course-work "Mastery of the subject matter" and "Connections within and across disciplines" came respectively in second and third position.

However, the reality is that not all students are cognitively prepared for such a rigorous context. The transition from high school or Cégep[1] to university is a time of great stress for students (Dickie & Farrel, 1991) and many find this period challenging and difficult. Arts and science undergraduates interviewed by Denison (1998) during their first semester at university reported that using the same study strategies they had used before (in Cégep or high school) did not produce the academic results they were accustomed to.

In addition to having inadequately developed cognitive abilities, many students enter their first year in university with a range of prior conceptions about their domain and ways to study it (Prosser & Trigwell, 1999). This has important implications in the classroom since it affects students at various levels of academic achievement across domains. Universities need to help their students to go through this transition and develop the appropriate study and thinking skills to successfully complete their post-secondary education. For higher-order learning to occur, students and professors need to be involved in a synergistic learning process within an appropriate instructional and institutional context (Donald, McMillan-Davey, & Denison, 1999).

Current Instructional Context in Undergraduate Physics

Traditional university science teaching might not always help students acquire appropriate conceptions of physical constructs and well-developed cognitive skills. The lecture method, as practiced in most physics courses, assumes that the student can accept clearly presented knowledge as given (Van Heuvelen, 1991). L. C. McDermott (1991a) advocates that:

> Traditional instruction in physics, both in high school and in introductory college courses, has been based on the instructor's view of the subject and on the instructor's perception of the student. .... Most teachers tend to teach as they have been taught.

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[1] The abbreviation *Cégep* stands for "Collège d'enseignement général et professionnel." In Québec, the Cégep is a mandatory step between secondary or high school and university studies. Cégep students usually take two years to complete a general program while vocational programs require three years of study.

> Very little inductive thinking is involved, the reasoning is almost entirely deductive; the student is not actively engaged in the process of abstraction and generalization. (p. 307)

Similarly, laboratory experiments are mostly limited to the verification of known principles or to testing or disproving a hypothesis or idea (Etkina, Van Heuvelen, Brookes, & Mills, 2002). Students typically have little or no opportunity to start from personal observations and experience the discovery phases and reasoning modes necessary for conceptualizing and formulating the principles under investigation. Another limitation of laboratories was discussed by Schauble, Klopfer, and Raghavan (1991) who concluded that "many teachers try to capture student interest by planning classroom demonstrations and experiments that include exciting and attractive effects" (p. 877). They also noted a natural inclination among students to think that the goal of the experimentation is the production of an effect, rather than the understanding of processes producing that effect. In such a situation, the potential of laboratories in providing an opportunity for students to contrast their predictions and the actual results in an effort to articulate and become aware of their own understanding (Clement, 1982) might not be realized to its fullest.

Nonetheless, physics students come to university with great expectations regarding their learning and their training. They expect the university to provide them with a strong foundation on which they will be able to build their career.

Roots of Interests in Advanced Electromagnetism

Physics is commonly considered a hard or paradigmatic discipline (Donald, 1993). The perceived abstractness of the concepts, the degree of logical precision essential in problem-solving, and the mathematical skills that are required to speak the language of physics are some of the factors which are likely to contribute to that judgment. Among the various sub-domains addressed in physics programs, electromagnetism appears to be especially demanding for students. Yet, it remains one of the least investigated fields of physics education.

Much of the empirical literature on physics education is on students' conceptions, carried out on mechanics and optics. In contrast, electromagnetism has received less attention although it is one of the most challenging topics in undergraduate physics. The existing body of research on learning in physics points to a common set of student misconceptions or alternative conceptions. This informs instructors about what are likely to be the difficult aspects of a given course and how to address them specifically in the classroom. However, no research seems to have addressed the potential role of students' more general conceptions about physics and approaches to learning and the way in which this influences the development of cognitive processes and problem-solving abilities. This question is particularly interesting when posed in the context of electromagnetism because electrical and magnetic phenomena are significantly less concrete than gravity or friction phenomena, both of which are commonly and personally experienced by students on a daily basis. Moreover, the bulk of the research on physics education at the undergraduate level focuses mainly on introductory courses taught in the first year. Very little attention has been devoted to more advanced undergraduate courses where students have had more experience as learners. In the second or third year of their undergraduate program, students are not experts or autonomous researchers but they are among the most experienced undergraduates. Most importantly, they are at a crucial stage of their programs, building their future careers and considering the job market and/or graduate studies.

Purpose of the Study

With these considerations in mind, this study examined the approaches to learning and perceived role as students of physics undergraduates enrolled in advanced courses of electromagnetism, during their second year of study. Evidence of the use of cognitive processes (i.e., metacognition, critical thinking, and physical intuition) and problem-solving abilities judged essential in physics were investigated twice: a) a first time within the students' regular teaching environment and b) a second time, after a small group of students had experienced a series of problem-based learning (PBL) activities. The problem-based learning (PBL) intervention was considered a promising approach to foster the development of these cognitive competencies, even if it was only implemented for a short period of time.

This study also sought to capture the nature of the cognitive actions and processes that the students engaged in when learning to solve electromagnetism problems in a PBL environment for the first time. Both the traditional and PBL instructional contexts were documented and assessed for their respective potential in fostering the development of metacognition, critical thinking, physical intuition and problem-solving skills.

Outline of Succeeding Chapters

The second chapter constitutes a review of the literature relevant to the study. It includes literature from the physics education, expertise, cognitive science, and instructional psychology research. The third chapter presents the methodological approaches used in the study. The fourth chapter addresses the results and their interpretation. The fifth and last chapter presents a general discussion of the implications and recommendations for future research and practice.

CHAPTER 2 – CONCEPTUAL FRAMEWORKS AND LITERATURE REVIEW

Introduction

Various bodies of literature were considered for this research because of their respective potential to provide new insights on physics teaching and learning and, more specifically, on the development of cognitive capacities and problem-solving abilities. First, the expertise and cognitive science literatures helped identify and clarify the nature of the desirable knowledge competencies and cognitive capacities for science and physics students.

Schwab's (1973) four commonplaces were used as a framework to organize the literature related to these desirable cognitive outcomes in terms of the: a) context, b) learner, and c) teacher. The fourth commonplace, i.e., the "content matter" was integrated within the "context" and "teacher" commonplaces rather than addressed separately. The *instructional contexts* in physics that can best promote the development of the cognitive abilities of interest were considered in the literature on instructional approaches. Lecture and problem-based learning were described from that perspective. The *students'* epistemologies and ways of learning were derived mainly from the physics education literature. The instructional psychology literature was reviewed as a context for discussing *professors'* practices and conceptions of teaching.

Finally, considerations on how to measure the desirable cognitive abilities of interest came mostly from the cognitive science and discourse processes literatures.

Expertise

A model frequently used to understand the learning process of advanced knowledge and capacities at the postsecondary level is the expertise model. Besides professional programs such as engineering and medicine, one of the fields often explored is physics expertise (Donald, 1992). This is a source that has the potential of identifying and explaining the process of developing cognitive processes and core competencies in general and physics problem-solving in particular.

Expert-novice Model

In all domains, some individuals seem to be more proficient than others. Some people are more skilful than others, some are faster, more successful, or perform at a higher level than their peers. One could say they are outstanding. Despite the fact that, in most circumstances, practice and experience greatly contribute to reaching an expert level, neither is a guarantee for achieving expertise. As a matter of fact, the majority, irrespective of their domain, will never reach a level of expertise (Dreyfus & Dreyfus, 1986b) no matter how many years they practice their skill or discipline. And, as is the case with learning, developing expertise is influenced by individual differences (Sternberg, 1998) and potentially by inherited traits or genetic factors.

It is generally accepted that expertise is associated with consistently achieving intended outcomes, representations or behaviours as opposed to "lucky" achievements due to peculiar circumstances. The beginning of research on expertise can be associated with the progress made in the field of artificial intelligence and cognitive psychology in the mid-sixties. What we can call a first generation of theories of expertise emerged in the era leading to the 1980s. During this period, among the most popular sub-domains for the study of expertise were (a) chess, with the studies carried by Newell and Simon (1972), Chase and Simon (1973), and by de Groot (1966) who was himself a chess master; (b) physics problem-solving, addressed in the work of Larkin, McDermott, Simon, and Simon (1980) and Chi, Feltovich, and Glaser (1981); and (c) memory, studied by researchers like Chi (1976) and Ericsson and Chase (1982). These individuals were pioneers in studying the cognitive processes of expertise. During this initial period, an expert was considered "someone particularly skilled at general heuristic search" (Holyoak, 1991, p. 301). Experts were perceived as people with specialized memory skills and inference patterns based on highly specialized domain knowledge.

The second generation of expert theories emerged following the work of John Robert Anderson (1983a, 1983b) with his ACT (adaptive control of thought) theory and his production systems. ACT is a theory of human cognitive functioning that addresses memory, inference making, and language comprehension. It assumes, among other things, that memory is non-erasable and, consequently, almost all forgetting must be due to retrieval failure (J. R. Anderson, 1976). This makes a fundamental distinction between procedural knowledge and declarative knowledge. An ACT production system consists of three memories: working, declarative, and production (R. D. Anderson, Kahl, Glass, & Lee Smith, 1983). Production systems represent knowledge states and transitions among these knowledge states and depict principles for computing activation levels for the knowledge structures (J. R. Anderson, 1990). A computer program was designed to simulate it and to try to prove the internal consistency of the theory.

Rosenbloom and Newell (1986) refined the idea of *chunking* in relation to expertise. The pioneering role of Jerome S. Bruner and George A. Miller needs to be acknowledged here. Many of the early developments of cognitive psychology originated with these two Harvard psychologists who founded the Center for Cognitive Studies in 1960. Bruner, Goodnow, and Austin's (1956) *A Study of Thinking* focussed on concept acquisition. The same year, in one of the most influential papers of this period, Miller (1956) addressed extensively the cognitive structure of the memory. Miller's claim was that over a short period of time, human beings could retain only about seven items in memory. However, if the items became coherent units or "chunks," this limitation of the memory system could be overcome.

Complex or high-level problem-solving became central to the study of expertise and served as a means to develop cognitive theories. Procedural knowledge learning, as opposed to only declarative knowledge memorization, became the focus of many studies (Holyoak, 1991). Attempts to define and characterize routine or automatized processes of experts were numerous (e.g., Chase & Simon, 1973; J. R. Anderson, 1982). The detailed procedure for protocol analysis, developed by Ericsson and Simon (1993), was elaborated during this period as a means of delineating automatized routines.[2]

The existing literature suggests that experts from different domains appear to share some common characteristics that somehow define what makes them experts as opposed to novices in their particular domain. These characteristics have been addressed by authors such as Chi et al. (1981), Chi, Glaser, and Farr (1988), Glaser and Chi (1988), Glaser (1989), Posner (1988), Ericsson and Smith (1991), and Sternberg (1998). Experts have a vast body of specific and highly organized knowledge from which they can draw systematically to perform efficiently in their area of expertise (Olson & Biolsi, 1991). The knowledge base of the experts is more abstract, more principled, and more organized than its equivalent in novices (Schraagen, 1993; VanLehn, 1996). The efficiency with which experts retrieve and make use of their knowledge base is also different from novices. Experts' cognitive performances are complex processes difficult to understand (Lesgold, 1988).

The ability to elicit and capture expert related behaviours and thinking processes has preoccupied researchers and the relevance of their findings to this study lies mainly in the extent to which they contribute to our understanding of problem-solving in physics. This literature is discussed in the next section.

Expertise and Skilled Performance in Physics

Anzai (1991) defines physics expertise as follows:

> Expertise in physics comprises the abilities of acquiring and possessing those theories [of the physical world], exploiting them for understanding and predicting new phenomena, developing new theories to explain the physical world from novel points of view, and designing new experiments to reveal unknown facts about the physical world, with the capacity of learning to acquire knowledge underlying these abilities. (p. 64)

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[2] Ericsson & Simon's original book had been published in 1984.

With this definition, one thinks of the winners of physics Nobel prizes as experts. People such as Albert Einstein have been the center of numerous studies attempting to characterize what expert physicists do differently that they are so outstanding. Other high achievers have been studied in controlled situations where they were presented with physics problems to solve. The problems were complex enough to allow experts' and novices' solutions to be distinguished from one another and analyzed in detail. Since the late 1970s, problem-solving has been a popular path to address expert-novice differences in physics. Table 1 presents some of the characteristics shared among expert physicists that were identified in the context of these studies.

Table 1
Characteristics of Physics Expertise

Characteristics of Expertise	Description / Implications in Physics
Knowledge organization and structure	• Physics experts' knowledge is organized into fast-access pattern recognition or encoding systems (Lesgold, 1988) • Physics experts have well-organized abstract knowledge for constructing abstract problem representations. Novices tend to have commonsense knowledge and weaker methods for solving problems (Anzai, 1991)
Proceduralized and goal-oriented knowledge	• Physics experts have strong mathematical skills (Larkin et al., 1980) • Experts usually work forward from the given to the desired quantities – novices often work backward (Larkin et al., 1980; Simon & Simon, 1978) • Experts do not need support in determining goals and sub-goals while novices need guidance (Simon & Simon, 1978)
Depth of problem representation	• Physics experts are able to translate verbal statements into the language of mathematics (Larkin et al., 1980) • Experts tend to represent physics problem in abstract terms (e.g., point-masses, frictionless surfaces, etc.) while novices use naïve concepts (e.g., ropes, slopes, etc.) (Anzai, 1991) • Experts can sort problems by the principle that provides a solution (e.g., Newton's 2nd law) while novices generally sort problems by keywords or visual configuration (Chi et al., 1981; Van Heuvelen, 1991) • Sorting problems and building a representation usually take longer to experts but they make few errors (Chi et al., 1981; Lesgold, 1988)
Automaticity and controlled processing	• Experts tend to follow a systematic sequence of steps, such as: a pictorial representation (a sketch which depicts the situation), a physical representation (graphs and force diagrams), a mathematical representation (quantitative solution) (Van Heuvelen, 1991)
Procedural performance analysis	• Experts have the ability to organize their knowledge according to principles selected to fit the current problem's anticipated solution (Schultz & Lochhead, 1988) • Experts have the ability to evaluate the probable validity of a physical model through an analogy or chain of analogies (Schultz & Lochhead, 1988)
Metacognitive and self-regulatory skills	• High achievers in problem-solving tend to generate self-explanation and self-monitoring statements more frequently than low achievers (Chi, Bassok, Lewis, Reimann, & Glaser, 1987)
Efficiency and performance	• Experts solve complex physics problems faster and more accurately than novices (Larkin et al., 1980; Simon & Simon, 1978) • Experts in physics are proficient at drawing diagrams and at making inferences from them. (Anzai, 1991)

As can be seen in Table 1, expertise in physics involves a range of superior skills and competencies. Nonetheless, there is a possible limitation of these studies in that they rely, for the most part, on lower level problem-solving tasks in order to describe the differences between novices and experts. These studies on physics expertise tend to use "classic problems" from introductory courses of mechanics. But, physicists do not typically solve written problems with a known solution on a daily basis. Experts are more likely to develop creative solutions than novices (Sternberg & Horvath, 1995) and unusual contexts can elicit or stimulate creative thinking and ingenious problem solutions more readily than familiar problems. Lesgold (1988) explains the crucial role of Albert Einstein's creative thinking in the context of his "thought experiments" when developing the relativity theory. His expert understanding of physics and intensely focused problem-solving would not have been enough to achieve such a result – he allowed himself to go beyond.

Studies of performances in unfamiliar situations appear essential to characterizing creative problem-solving by experts (Pelletier & Shore, 2000) and to providing a more realistic understanding of what physicists really do. Despite their relevance, these types of studies are generally non-existent. Another missing piece of information within the physics expertise literature seems to be any indications on how to help novices (i.e., students) progress toward expertise in physics, in general and, more specifically, how professors can foster the development of expert-like cognitive abilities and problem-solving skills among their students.

A number of studies have attempted to describe the development of expertise in general. They are discussed in the next section. However, the resulting description seems to offer limited direction or concrete advice on how to best support university students' initial steps on the road to expertise.

Development of Expertise

Expertise is generally seen as a relatively stable characteristic of an individual placed in a relevant context. However, this does not mean that expertise is fixed in time and incompatible with progress. "[T]he journey to expertise is unceasing" (Alexander, 2003, p.10). In a similar perspective, Sternberg (1998) refers to expertise as "typically not at an end state but a process of continual development" (p.11). From that view point, he reconciles two bodies of literature that were for a long time separate: the literature on *abilities* and the literature on *expertise*. Sternberg presents skills and abilities as a form of developing expertise rather than as innate and fixed features.

In the 1980s, John Robert Anderson (1983b) proposed three stages for cognitive skill development: a declarative stage, a knowledge compilation stage, and a procedural stage. These stages serve as levels of domain expertise and Anderson described them as follows. "In the declarative stage of skill development, domain activities are slow and prone to error" (Royer, Carlo, Dufresne, & Mestre, 1996, p. 375). In the knowledge compilation stage, the domain-relevant information is "increasingly organized and differentiated" (p. 375) as the interrelations between the declarative statements become stronger and the domain network more complex and elaborate. Finally, the procedural stage of skill development corresponds with a process whereby knowledge is organized into increasingly larger chunks. Similarly, the conditions under which specific chunks of information are activated become both more diversified and refined. The process of moving from one stage to the other for a particular individual occurs over an extended period of time. The final stage is characterized by a reduced cognitive load, which helps the expert deal with higher level cognitive activities than a novice. This representation of different stages of learning and integration of knowledge along with the different degrees of proceduralized and compiled skills is also supported by Glaser (1989). Anderson's learning theory implies that extended practice is essential to learning (Lesgold, 1988).

In the first chapter of their book *Mind over machine*, Dreyfus and Dreyfus (1986a) defined five stages of skill acquisition, leading the novice to expertise. Although differently defined than by Anderson, these stages are not incompatible. Dreyfus and Dreyfus present them from the learner's perspective rather than from the skill-to-be mastered perspective. Their classification includes the following: novice, advanced beginner, competent, proficient, and expert. These stages are mutually exclusive. As the novice progresses and improves his/her performance through practice, he/she gains proficiency to eventually engage in skilful performance. Through that process, a library of distinguishable situations is built-up, based on the acquired experience.

Among the models of expertise, Sternberg (1998) (see Figure 1) offers an interesting perspective on the different variables that have an impact on the development of expertise. It includes the motivation that the individual needs to have and sustain in order to move ahead on the path toward expertise. It shows the way in which the major elements (metacognitive skills, learning skills, thinking skills, knowledge, and motivation) interact with one another in a particular context and environment. Moreover, it is general enough to be useful in basically all domains. Two aspects are particularly noteworthy in this model. One is that despite being synthetic, it effectively addresses some of the essential features of developing expertise. The other is the iterative loop between expert and novice. The latter clearly shows that expertise occurs at many levels and each time an individual engages in a new domain or even a new aspect of a known domain, he/she goes through the cycle again.

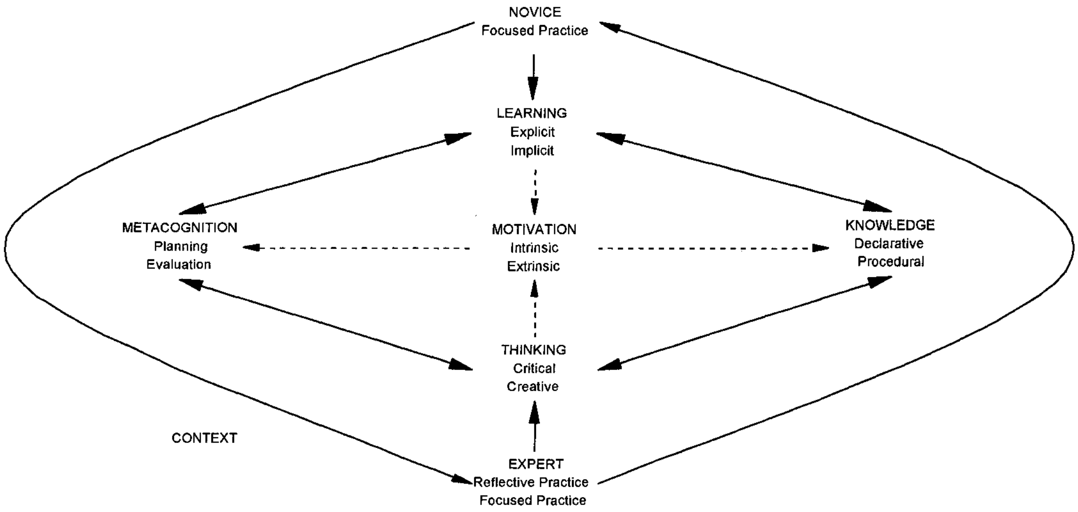

Figure 1. Developing-expertise model adapted from Sternberg (1998)

Interestingly, novices are individuals with the potential to become experts. In other words, and as stated by Posner (1988), ordinary people can potentially progress toward expertise if they can create and maintain the motivation needed for long-continuing training. These are, however, limitations to this development. Generally speaking, the “reaction time for retrieving information improves with practice” (p. xxxii). However, there is no evidence in the literature that being exposed to numerous trials will systematically cause a specific performance to become automated up to the level of expertise. The role of practice has been debated and “one can no longer assume that superior performance is automatically achieved merely as a function of practice” (Scardamalia & Bereiter, 1991, p. 30). Practice still is one of the major independent variables in the acquisition of a skill, but individual differences also play a definite role in the building of expertise.

Since the 1980s, expertise has been described as highly domain-specific. Despite communalities between experts in general, an expert in one domain is not expected to automatically excel in another domain. Although it might sound simplistic, this statement has a lot of implications. The importance of the factual and procedural knowledge was mentioned previously. Expertise in a specific domain actually is highly linked to the individual’s factual (i.e., the concepts relevant to domain and the relationships among them) and procedural knowledge (i.e., the knowledge of the “how to” generally acquired through practice (J. R. Anderson, 1976)) in the domain as well as to the explicit and tacit domain knowledge. Consequently, there is very little knowledge and few skills or abilities that can effectively be transferred directly from one domain to another (Chi et al., 1988).

In the case of physics, instructors and researchers alike agree that problem-solving is a valuable “vehicle for learning physics” (Huffman, 1997) as well as an essential ability to be developed by students and future physicists. However, problem-solving is a multi-layered and complex competence that most students will not develop unaided (Bolton, Keynes, & Ross, 1997). Unfortunately, even after specific instruction on problem-solving, many students continue to use novice problem-solving strategies and techniques rather than the more advanced (more expert-like) approaches they were introduced to (Maloney, 1994). Sternberg (2003) goes further and asserts that conventional methods of teaching, at best, create pseudo-experts and that students’ expertise, when present, tends to be only content expertise which does not correspond to the type of expertise that will be asked of them in a professional context.

In other scientific domains, such as mathematics, chemistry, biology, or computer science, problem-solving has been studied as well (e.g., Confrey, 1990). From that research as well as from studies on chess, similar characteristics of expertise can be derived. And in all those domains as well, controlled problem-solving tasks (generally inspired by introductory course content) have been used frequently to study the development of expertise.

Problem-solving in physics shows many similarities with problem-solving in other domains. In fact, in some professional contexts, such as medical diagnosis, problem-solving is what personnel do all the time. That body of literature sheds a very interesting light on problem-solving tasks that professional physicists are dealing with: i.e., non-routine procedures. Physicists do not typically solve "classic" problems – extracted from introductory mechanics, optics, or electricity – for which a clear and defined solution is always known. Oftentimes, physicists have to determine themselves what is the problem worthy of their investigation. It is in this regard that their expert judgement comes into play in the first instance.

While we have a fair idea of what the model of an expert physicist and problem-solver should look like, this body of knowledge has not penetrated in actual science teaching. A more concrete understanding of how to best support and foster students' transition toward expertise, including the development of superior cognitive processes and problem-solving abilities, though most desirable, is not available. "Research must specify how to promote transitions or changes in competence in different learning situations" (Lajoie, 2003, p.21).

For this study, the cognitive science body of literature was also considered as a potential source of explaining how the students' cognitive processes and problem-solving abilities develop and can be fostered.

Problem-solving Abilities and Cognitive Processes that are Desirable in Physics

Among the various types of strategies used in physics and other "hard" sciences to help students develop their thinking skills and get a better grasp of the concepts being taught, solving problems has probably been the most broadly and systematically used for decades. It is possibly one of the most flexible yet complex strategies that can be utilized to provide students with opportunities to refine, think about, and apply their knowledge.

Problem-solving Models and Theories

A skilled problem-solver has necessarily mastered a number of cognitive abilities. Donald (2002) uses an interesting analogy: "problem-solving includes critical thinking processes but also implementation or testing; the difference between *critical thinking* and *problem-solving* is analogous to comprehending versus doing" (p. 24). Similarly to Green (1966), Newell and Simon (1972), and more recently Dunbar (1998), this study conceptualizes problem-solving as a process. As a process, it implies a set of steps and calls for the use of various skills.

Problem-solving is a complex activity; an individual engaged in problem-solving draws on memory, knowledge, and various cognitive processes in order to move from an initial state to a goal state via actions and operations within a task environment (Dunbar, 1998). As suggested by Newell and Simon (1972), problem-solving is a search for a path through the problem space that will lead to the goal state (Dunbar, 1998). The problem space is composed of all the sequences of possible moves or steps available to the problem solver when trying to reach a solution (Hayes, 1989). In other words, the problem space comprises all the different ways that a problem can be solved (Dunbar, 1998)

Typically, a problem-solver's representation of a problem is only a fraction of the possible states of a problem at a given time. In fact, individual differences play an important role in the variety of problem representations. For example, one's previous experience or level of expertise in solving problems of a similar nature will influence one's degree of success in identifying what to pay attention to, how to represent the problem, how to search for a solution, or all three (Hayes, 1989). J. R. McDermott and Larkin (1978) have shown that novices in physics are likely to have problem representations or schemas that are tied to concrete aspects of the problem situation (e.g., "spring problem" and "balance problem" schemas), whereas experts are more likely to have schemas tied to abstract physics principles (e.g., "energy" and "moment of inertia" schemas).

These schemas are also called *internal representations*; they constitute a personal interpretation of what the problem is about and what the goal to be achieved is. Representations can also take an external form. Sketching, drawing, making diagrams, jotting down lists, writing down symbols or equations are all examples of external representations which correspond to parts of the internal representation of the problem. External representations can prove extremely useful when solving particularly complex problem (Hayes, 1989). They also supplement the working memory. One problem can have various representations. Different individuals will develop different representations and, for a single individual, representations can change and evolve as the problem is being solved.

In addition to variations attributed to individual differences, problems themselves can vary. They can be *well-defined* – in which case they have a definite initial state and known goals and operators (Dunbar, 1998) – or they can be *ill-defined*, in which case they cannot be solved unless specific actions are taken to define them better (Hayes, 1989). Since there is a considerable array of ill-defined problems that students are exposed to in their undergraduate education, we would ideally want them to develop appropriate representations in order to eventually become autonomous problem-solvers.

The graphical representation below, Figure 2, illustrates the processes involved in problem-solving. Most processes include a feedback loop. Problem-solving is rarely a straightforward endeavour, even for experts, but rather an iterative process. While engaged in solving a physics problem, a solver (who could be a novice or an expert) builds a personal representation and comprehension of the problem. The solver needs to identify the concepts being addressed and to understand them in a qualitative sense, in the broad as well as specific contexts of the problem. Likely, the solver might draw links with similar problems, cases, or examples he/she has already dealt with in the past. Then, a very important aspect is going to be the retrieval of the factual and procedural knowledge that the solver has of the concepts involved. At this point, the solver is already trying to select a method or procedure to apply, in order to solve the problem in a more quantitative manner. Some paths might be rapidly withdrawn or might be pursued in a "trial and error" fashion. The accuracy and the speed with which a correct solution is obtained for a specific problem will vary from one individual to another according to the level of expertise.

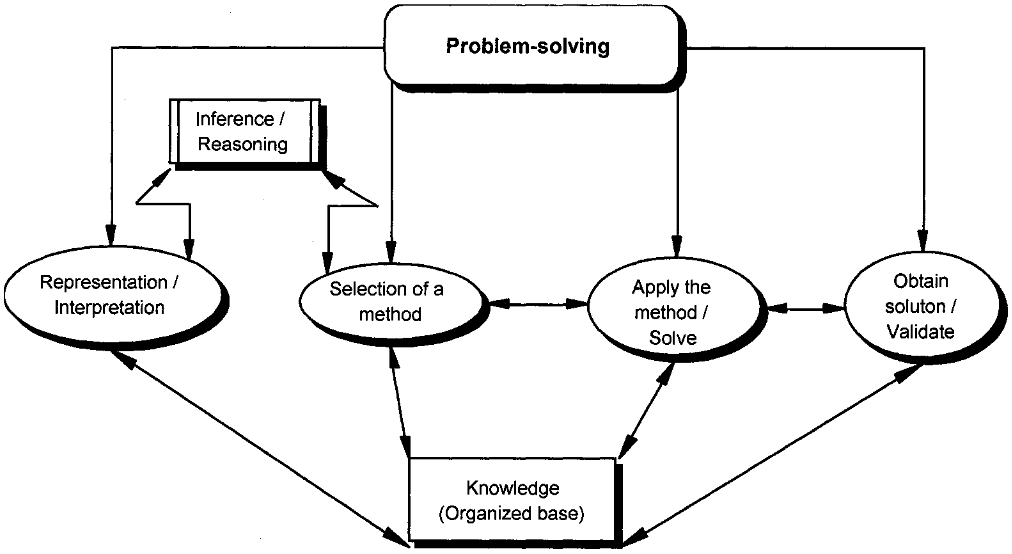

Figure 2. Problem-solving process

In addition to robust problem-solving abilities, other cognitive competencies appear essential in physics. There are discussed in the next section.

Cognitive Processes in Physics

Students who choose to study physics are typically confronted with a range of demanding courses which aim at challenging and developing their cognitive abilities.

Beyer (1997) summarizes the essence of what is expected of undergraduate physics students:

> Thinking of high quality, in short, is the inclination and ability to carry out a wide range of cognitive (thinking) operations – including especially complex, higher-order operations – in a rapid, accurate, expert, self-critical, and self-correcting manner; in a wide variety of contexts, including unfamiliar ones; and in a comfortable and confident manner to produce sound, accurate thinking products. (p. 4)

The development of such superior skills is expected to lead students toward competence and autonomy in the physics domain. Some of the competencies are shared by competent and expert physics problem solvers. For example, physics problem-solvers have superior metacognitive skills, critical thinking abilities, and physical intuition. These cognitive processes are highly desirable for effective *problem-solving*. Schultz and Lochhead (1988) qualify expert physics problem-solvers' metacognitive skills, that is their ability to monitor and question their reasoning, as "a constant searching for other perspectives that may support or disconfirm previous ones" (p. 8). Moreover, a problem-solver with good physical intuition "can often solve difficult problems rapidly and without much conscious deliberation about a plan of attack" (Larkin et al., 1980). These specific cognitive processes and skills are addressed below.

Metacognition

Possibly one of the most empowering dimensions of thinking, metacognition has been the central topic of numerous programs of research over the years (Brown, Bransford, Ferrara, & Campione, 1983). Vygotsky (1962) described metacognition as a skill involving two processes: reflective awareness and deliberate control. Metacognition thus refers to a person's knowledge and control of his/her own cognitive processes (Bruer, 1998). In other words, metacognition is the learner's awareness of his/her own cognitive processes and the ability to regulate them by using skills such as planning, monitoring, and checking.

Cognitive processes such as *metacognition* are crucial to effective thinking and problem-solving (Pellegrino, Chudowsky, & Glaser, 2001). As stressed by Newell (1990), two critical aspects in problem-solving are applying a strategy to a specific problem and selecting and monitoring a strategy. Indicators of metacognition, among strong learners, appear to reside in the individual's: (a) competence to explain and justify the strategies they intend to use in order to solve a problem; (b) ability to apply the selected strategies, and (c) capacity to readjust if the plan is not working as expected (Pellegrino et al., 2001).

The outcome of utilizing well developed metacognitive capacities can be the selection of alternative strategies. "Good problem solvers will try another strategy if one is not working, while poor problem solvers will hold to a strategy long after it has failed" (Pellegrino et al., 2001, p. 78). Less competent problem-solvers tend to monitor their thinking only sporadically and generally in a less effective way (Chi et al., 1987).

Critical thinking

Another cognitive process is *critical thinking* or the "reasonable, reflective thinking that is focused on deciding what to believe or do" (Vockell & van Deusen, 1989, p. 5). Students with effective critical thinking capacities are able to judge a situation accurately and have a critical appraisal of the information they have access to. Moreover, they can critically examine their own work and thinking process.

To engage students in a critical evaluation of the information at hand, Beyer (1997) suggests providing them with problems that contain various non-essential data. Using this type of exercise can also help document the extent to which students get distracted by irrelevant information provided in the text of the problem. Another approach to elicit students' critical thinking consists of a "categorization experiment" (Mestre, Dufresne, Gerace, Hardiman, & Touger, 1993) where the students compare problems on the basis of their surface and deep structures. More specifically, students are asked to choose the right (or best) plan and solution from a set of possible answers, which Wright

(2001) calls "evaluation of rival cases." The potential of the exercise in stimulating critical thinking is significantly increased when students are required to evaluate each plan and solution (and to detail and elaborate on whether or not each is the best) rather than to simply select a single correct answer. In this instance, it is referred to as "multi-rating items" (Paul & Nosich, 1991).

Physical Intuition

Another important cognitive ability is the capacity to capture the essence of a problem and not simply to understand its external features. Think aloud protocols have shown that physics experts often refer to using their *physical intuition* to solve problems as a sort of "feeling" or "sense" of what would be the appropriate way to go about solving a particular problem (Larkin et al., 1980). Dreyfus and Dreyfus (1986b) discuss intuition in general and refer to it in different ways in their book: "a kind of enlightened guessing" (p. 29); "the chess master's almost instantaneous understanding of chess positions and accompanying sense of the best move" (p. 33, when referring to Herbert Simon's studies on chess masters); or "the truly imaginative act for which there is no detectable historical precedent" (p. 40, as a part of a section interestingly entitled "Beyond Rationality").

From a similar perspective, Clement (1994) defines *physical intuitions* as concrete expectations embodied in a schema and which "stand without further explanation or justification" (p. 209). Prior knowledge, even incomplete or fragmentary, appears necessary for intuition to take place. In addition, intuition seems to be an integral factor in scientific and mathematical discovery (Vaughan, 1979). One of Einstein's famous quotes is an illustration: "There is no logical way to the discovery of these elemental laws. There is only the way of intuition, which is helped by a feeling for the order lying behind the appearance" (n.d.).

These definitions have in common an "educated guess" component. In other words, though intuition seems to happen suddenly and take the form of an involuntary viewpoint, it also appears to be grounded in existing knowledge or in a new rearrangement of known facts and data in a problem-solving context.

The psychology literature brings a nuance to the definition of intuition through its unconscious and instinctive dimensions, not depending upon cognition and rational or logical analysis. Carl Gustav Jung stated that "Intuition is perception via the unconscious" in his classification of psychological types[3].

In the context of this study, an attempt to discuss these problem-solving abilities and cognitive skills would not be complete without also addressing how the instructional psychology body of literature on instructional approaches could contribute to the learning process. The lecture and problem-based learning approaches to teaching were reviewed as two potentially effective instructional contexts conducive to the development of cognitive processes and problem-solving skills in physics. The role of laboratory experiments is acknowledged as well in the next section, although laboratories were not a part of this study design. The specific course of advanced electromagnetism that was the focus of this study did not include a laboratory component.

Instructional Contexts

This section attempts to shed light on what the features of desirable instructional contexts could be in physics. For decades, if not for centuries, science teaching in general has been associated with lectured-based curriculum (Hativa, 2000). There are indubitable advantages and strengths to lectures for covering massive amounts of theoretical content in a limited time and, often, in front of large groups of students (Frederick, 1986). However, this instructional context is generally characterized by a lack of participation and cognitive engagement on the students' side. A number of alternatives or variations to

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[3] Jung's typology includes two attitude types (i.e., introvert and extrovert) and four functions (i.e., thinking, feeling, sensation, and intuition). His typology was completed in 1921 under the title: "Psychological Types" (Jung, 1971).

traditional lectures have been developed and can significantly enhance the students learning experience in lectures.

The laboratories traditionally bring a "hands-on" dimension or complement to the lectures during which students can interact more easily among themselves and with the instructor. However, the students do not always understand the purpose of experiments which limits the potential of laboratories for meaningful student learning. Moreira (1980) concluded that students perceived their physics laboratories as isolated events, disjointed from the theoretical concepts presented in the lectures. The fact that not all courses are associated with laboratories in most physics programs might contribute to this perception. For instance, no laboratory sessions complemented the Electromagnetic Waves lectures that were observed in the context of this study. The laboratories the students attended during that semester pertained to modern techniques of measurement along with the use of computers in performing experiments and analysing data.

The limitations of both the lectures and the laboratories are addressed by another instructional context that has a significant potential for physics teaching: problem-based learning (PBL). PBL offers an interactive and dynamic context for students to become actively involved and accountable for their learning. These instructional contexts are reviewed in the next section.

Lectures

"Effective lecturers combine the talents of scholar, writer, producer, comedian, entertainer, and teacher in ways that contribute to student learning" (McKeachie, 1999, p. 66). The lecture is probably the most common and broadly used instructional approach in physics. This teaching strategy feels comfortable and natural for many science professors mainly because it corresponds to the instructional context that they most likely have experienced themselves when they were students. This approach to teaching also provides the professor with considerable control on the selection of the content (Hativa, 2000), the delivery, and outcomes as he/she is the main actor.

Lectures remain powerful communication tools in many situations. In both large and small groups, for example, they can allow the instructor to effectively address a large number of concepts in a short period of time (Saroyan & Snell, 1997). They are flexible enough to accommodate the varied and changing needs of audiences which is important in the face of student diversity (Saroyan, 2000). When they are well structured and articulated, they provide a meaningful organization of the content (McKeachie, 1999), especially in the form of summaries. Clear lectures help students to integrate the content (Saroyan, 2000) and can serve as modeling opportunities for thinking, interpreting knowledge, and problem-solving (Hativa, 2000).

These documented strengths of lectures show what a beneficial instructional approach it can be in physics classes; "under the right conditions, this method can work" (Saroyan, 2000, p.90). The right conditions, however, imply the presence of essential organizational and communication skills on the part of the lecturer, including clarity of expression, preparation and quality of the organization, to ensure an effective lecture, enthusiasm and expressiveness to maintain students' attention and motivation (McKeachie, 1999). In these conditions, lectures can be engaging and even interactive (Frederick, 1986).

Nonetheless, there are also major limitations to the typical lecture format. Some have severely critiqued lectures and documented their tendency to keep students passive. Lectures make it more difficult for faculty to employ active learning methods (Braxton, Milem, & Sullivan, 2000) and do not promote the autonomous construction of the students' own knowledge (Hativa, 2000). From the same perspective, the range of cognitive functions invoked in lectures (e.g., listening, note taking, interpreting) remains limited (Biggs, 1996) and opportunities for critical thinking and analyzing rarely occur in typical lectures (Saroyan, 2000). Moreover, Redish (2003) argues that many lecturers in physics do not expect their students to follow the pace in regular lectures. A recurrent reproach about the lecture is its impersonal nature, especially in large lecture halls (Hativa, 2000) where individual students disappear in the crowd.

K. K. Perkins and Wieman (2005) recently investigated the impact of seat location in large lecture halls on physics students' performance. There is a popular belief about the differential seating patterns often observed in classrooms as being simply a reflection of the students' respective seat location preferences (i.e., weak students tend to sit at the back of the classroom while stronger students prefer to sit at the front). The authors rather suggest that the seat location itself contributes to whether a student does well or poorly in a physics lecture. K. K. Perkins and Wieman's (2005) results, after reversing seat locations from front to back in a physics lecture hall halfway through the term, tend to show that the seat location had a significant effect on students' attendance, grades, and belief about physics, despite the instructors' efforts to engage all students equally in the lectures. The further the original seat from the front of the classroom, the lower was the attendance over the semester. Similarly, the fraction of A's decreased steadily as the original seat location was further from the front.

A number of innovative endeavours have been developed and can foster interactions in lectures, particularly in large auditoriums where interactions with students tend to be challenging. It can be noted that such improvement or addition to lectures do not constitute the norm. In other words, the interactive lectures described in the next section implement many of the established characteristics of effective lectures (see Centra, 1993) already mentioned while fostering students active participation. As such, the potential of these interactive lectures cannot be ignored but they are not typical or representative of lectures in general.

Interactive Lecture

Ramsden (1992a) nuances the notion of engaging teaching by distinguishing it from entertainment:

> While sterile and lifeless teaching is hardly conducive to the development of understanding, colourful presentation is by no means sufficient for effective student learning. A good performance is not necessarily good teaching. In fact, an

> entertaining lecturer may leave students with a sense of having been entertained, but with little advancement of their learning. (p.74)

Three types of interactive lectures are reviewed in this section because of their potential to stimulate students' active participation and learning while still taking place in regular classrooms (i.e., not needing a laboratory setting in the way the McDermott's (1996) Group 'Physics by Inquiry' would). These three interactive lectures offer significant improvement compared to more typical lectures in terms of the quality of the student learning. Redish's (2003) "active-engagement student-centered environment" is considered first. Mazur's (1997) Peer Instruction is presented next followed by the in-class voting systems.

Redish's active-engagement student-centered environment.

For what Redish (2003) calls an "active-engagement student-centered environment", the first and essential component is a classroom where tables and chairs can be moved around to allow for team work. Similarly, spaces between the stations must provide easy access to each group for the teacher or facilitator who monitors and guides students' work.

As long as the furniture can be moved, such a setting can easily be attempted even in classes with large enrolment at no extra cost. In the case of particularly large groups, it might be necessary to consider the training of assistants to monitor students' work and ensure timely feedback. This type of classroom organization brings a realistic variation to traditional settings in lectures and is flexible enough to be used only sporadically if needed. Within this classroom setting, a number of instructional approaches (e.g., demonstrations, tutorials, etc.) can be efficiently implemented to accommodate varied learning objectives. The physical setting is there to facilitate the process. One well adapted strategy within this physical setting is called "Peer teaching" (Mazur, 1997).

Mazur's peer teaching.

A typical Peer Instruction (Mazur, 1997; 2001) class is constituted of three or four brief presentations of ten minutes each addressing key concepts. Each presentation is followed by a "ConcepTest", generally composed of multiple-choice questions. Immediately after a "ConcepTest", the students are given an opportunity to explain their reasoning to each other. The answers of all students are tallied to inform the professor of the source of students' conceptual difficulties. The percentage of good answers usually increases after the Peer Instruction (Mazur, 1993). Because of the time consuming nature of the Peer Instruction approach, the number of topics covered, compared to that in the traditional instruction, sometimes need to be reduced as a consequence. Because the emphasis is on deep learning, a quick and surface coverage of content would not be compatible with Peer Instruction. More over, the "ConcepTests" are central to this approach and developing good ones require time and careful design (Mazur, 2002).

Voting systems.

Electronic personal response systems or "voting machines" have been used for about a decade now. Dufresne, Gerace, Leonard, Mestre, and Wenk (1996) found the classroom communication system they used (i.e., Classtalk) with physics students at the University of Massachusetts to be engaging students in active learning during the lectures and enhancing the overall communication within the classroom. Steinert and Snell (1999) reported positive results as well when using a similar system in medicine: (a) audience attention was aroused and (b) students received immediate and anonymous feedback on their knowledge. Bensky (2003) presented such a computer-controlled in-class feedback system as the ideal complement for Mazur's Peer Instruction. Draper and Brown (2004) noted that the benefits for the quality of the interactions in the classroom tended to increase with the lecturer's experience with the device. Recently, new individual wireless-keypads have been successfully used as in-class polling systems by Reay, Bao, Li, Warnakulasooriya, and Baugh (2005) in an introductory electricity and magnetism course to enhance learning as well as interactivity. These devices provide instantaneous voting summaries that, through students' answer to especially designed multiple-choice questions, reflect the level of class understanding.

In response to the high costs associated with such electronic voting machines, the need for technical support, and the specific training of faculty members, Bostock (2004) patented an alternative he called "CommuniCube". Made of foam or simply of plasticized cardboard, his ten-centimetre cube is cheap and does not require any technical knowledge from the instructors or students and is more convenient to operate than flash cards. The students rotate their cube to show a different color for every answer they can give (one to five options) for each multiple-choice question. The instructor, an assistant, or even students can easily count the brightly coloured squares or estimate percentages in large lecture halls to quickly return feedback to the group. The results of his research in varied domains include increased motivation and participation among students along with an improved level of overall students' satisfaction. Faculty members using the device also reported an increased confidence in their ability to immediately adjust to their students' instructional needs, as a result.

The results achieved with these interactive approaches and devices show clear potential for engaging students in more interactive lectures. However, other instructional approaches can go much further in terms of students' participation and for initiating authentic and multifaceted problem-solving activities.

Typical Laboratories

"Almost as a matter of dogma, laboratory work has long been accepted as an integral and vital part of science teaching" (R. T. White & Tisher, 1986, p.880). Concrete experience is broadly recognized as a valuable and effective method to approach scientific concepts. In addition, laboratories help develop familiarity with equipment, measures, and research tools (McKeachie, 1999).

In laboratories, students usually form pairs or trios to perform scientific experiment in especially equipped facilities. By nature, laboratories provide students with numerous opportunities for constructive interactions among themselves and with the instructor. These are features generally appreciated by students. However, the activities of the students are usually organized around a pre-determined experimental protocol that the students need to follow closely or reproduce. Even at the university level, the students are rarely provided with the opportunity to test themselves their predictions from a guess or from a theory (Tiberghien, Veillard, Le Maréchal, & Buty, 2001) which limits the potential of laboratories for the development of the students' problem-solving abilities (Garrett & Roberts, 1982).

Problem-based Learning (PBL)

A potentially powerful and increasingly popular approach attempts to refresh both the instructors' and the students' roles in the teaching and learning process by making the problem the starting point of learning. This approach, referred to formally as *problem-based learning (PBL),* requires that the students be accountable for their learning. The origins of PBL are rooted in the criticisms made, in the 1960s and 1970s, of the traditional health science education. At the time, it was alleged that there was excessive emphasis on memorization and this did not help students develop the problem-solving skills required in their professional practice (Wilkerson & Gijselaers, 1996).

PBL has evolved through the years and various trends or models have become associated with specific institutions. A few of these distinctive approaches to PBL will be presented briefly in a forthcoming section. However, despite the existing variations in the conceptualization and applications of PBL from one institution to the other, central characteristics have remained the same and they will be reviewed first.

General Characteristics of PBL

Barrows (1996) summarizes and provides a core model or basic definition of PBL in the following manner:

- Learning is student-centered;
- Learning occurs mainly in small student groups;
- Teachers [and instructors] are facilitators or guides;
- Problems form the organizing focus and stimulus for learning;
- Problems are a vehicle for the development of problem-solving skills;
- New information is acquired through self-directed learning.

PBL also addresses many of the criticisms of current science education (Allen, Duch, & Groh, 1996). With PBL, the development of learning communities (Duch, 1996) is fostered within small groups through cooperative work, and collaborative knowledge building (Frederiksen, 1999), along with better interpersonal skills – which brings a new dimension to the traditional competitiveness and isolation often associated with science courses. The improved interpersonal skills include the ability to communicate clearly (Dahlgren, 2003) and the ability to work respectfully and productively with others (Kolmos, 1999) drawing upon evidence to provide a basis for argumentation.

PBL problems are contextualized and based on real-world situations and this tends to reduce the abstractness of the concepts addressed. Process and content are closely linked. As argued by Watson (2002), some of the desirable outcomes of this approach are that students develop the ability to gather and evaluate new information, think critically, reason effectively, and solve problems efficiently.

In addition, because not all information to solve the problem is given initially in PBL groups, students need to identify, find, and use the appropriate resources, much in the same way that professional scientists would do. This initiation to the real world or professional acculturation that is facilitated by PBL is explained by Frederiksen (1999):

> A central assumption of PBL is that, for students to develop expertise in a professional domain, they must not only acquire a rich body of conceptual and procedural knowledge and facility in applying it to analyze and solve authentic problems but they must also become proficient in functioning within the kinds of social contexts in which groups of professionals typically collaborate to solve problems. (p. 135)

The ideal tutorial group is composed of four to seven students and one tutor (Kelson & Distlehorst, 2000), but expert PBL tutors are able to deal with larger groups within which smaller groups of students are created.

PBL normally starts with an engaging problem and through the guidance and scaffolding of the facilitator, it can contribute significantly to fostering the students' self-directed learning abilities (Hmelo & Lin, 2000). The curriculum is structured in thematic blocks that address the overall subject framework (De Graaf & Kolmos, 2003). It is often said that students are led to "learn how to learn" with PBL. It also provides students with an opportunity to develop strong problem-solving methodologies including the definition of the problem, the gathering and evaluation of the information, and the development and assessment of a solution.

Capon and Kuhn (2004) summarize the mechanism by which problem-based learning achieves positive effects on students:

1. superior acquisition of new material, because of previously activated knowledge structures to which it can be connected;
2. superior recall of new material, due to an increased number of retrieval paths;
3. superior integration of new material with existing knowledge structures, leading to restructuring and enhanced conceptual coherence.

A number of studies do not support the idea that students gain a more important amount of factual knowledge when content is approached with PBL, compared to non-PBL courses (e.g., Dochy, Segers, Van den Bossche, & Gijbels, 2003; Verhoeven et al., 1998). They generally conclude that PBL and non-PBL types of instructional contexts are comparable from that perspective. However, most agree on the superior retention period displayed by the PBL students (Dochy et al., 2003).

Specific Models of PBL

Among the institutions where PBL is a usual mode of instruction, either within specific study programs or across their campus, some tend to distinguish themselves with specific characteristics. Four of these institution models of PBL are overviewed in the following sub-sections.

The original McMaster model of PBL in medical education.

The pioneering role of McMaster University (Hamilton, Ontario, Canada) in developing problem-based learning in medical education in the mid 1960's is internationally recognized. In reaction to the explosion in medical information and the rapidly changing demands of future practice, the Faculty of Health Sciences at McMaster University introduced a tutorial process, student-centered and interdisciplinary, around which they structured their medical curriculum (Boud & Feletti, 1997). Their motivations included a will to address recurring criticisms about the health sciences education, including: (a) emphasis on memorization, (b) fragmentation of knowledge, and (c) failure to equip graduates with life-long problem-solving skills (Wilkerson & Gijselaers, 1996).

In addition to being recognized as the precursor in the domain, McMaster University distinguishes itself by its approach oriented toward community-based learning (Boud & Feletti, 1997). McMaster formed a Network Community Oriented Educational Institutions for Health Sciences through an association with other medical schools.

The Aalborg model for natural science and engineering.

In 1974, Aalborg University (Aalborg, Denmark) was founded. Aalborg introduced entirely problem-based project-oriented natural sciences and engineering study programs. Aalborg University's innovation was to implement project-based instruction in *all* of its study programs, with a focus on natural sciences and engineering instead of medicine. Project-based education needs to be distinguished from problem-based learning (PBL), although both emphasize the learning process instead of the teaching process and are consistently utilized at Aalborg University. Project-based education is product-oriented (Kolmos, 1996). A project typically lasts for one complete semester and includes learning objectives pertaining to varied topics and even disciplines as well as to the documentation of the learning process in the form of a project report. Because of its complexity, project-based education is supported by a number of courses and complementary lectures (Kjersdam & Enemark, 1994). Problem-based learning is process-oriented and its result is mainly new and more integrated knowledge (Kolmos, 1996). Problem-based learning can be embedded within a project and generally takes less time and focus on a much narrower scope of topics than a project.

One of the characteristics of the Aalborg approach is the close collaboration and cooperation that the University maintains with industries (Fink, Enemark, & Moesby, 2002) to ensure that students engage in authentic projects that are representative of the engineering profession. Whether they are in a project-based or problem-based phases of their program, students at Aalborg work and are assessed in groups (e.g., they defend their project as a group). Each group has access to *its own* office space and is supervised regularly by at least one tutor. During their first year, in addition to a project-tutor who is highly-knowledgeable about the project topic(s), each group is also supervised by a PBL-process tutor. The process tutor helps the students become comfortable with working in groups and organizing their work, irrespective of the topics addressed in their project. The training of the tutors is consequently emphasized in the Aalborg model and only faculty members can be tutors (i.e., either process-related or topic-specialist tutors).

The Maastricht model of PBL.

Maastricht University (Maastricht, Netherlands) opened around the same time as Aalborg. A few years later, the Maastricht Faculty of Medicine became the second worldwide to implement problem-based learning as its dominant instructional approach in medical education. Similarly to the McMaster model, the Maastricht model of PBL is divided in periods or blocks during which a single theme is addressed. Each block is multidisciplinary (within the theme) and often organized around cases. The work is done in groups at Maastricht but the evaluations are done via individual examinations (Kolmos, 2002). Assessments take place at the end of each block. Four times a year, the students do a "progress test." All study programs are now problem-based in Maastricht. Social skills are particularly valued in Maastricht and self-motivation is the cornerstone of this education system (Maastricht University, 2005).

The Sherbrooke model of PBL.

In Québec, the Université de Sherbrooke (Sherbrooke, Québec, Canada) has been a leader in problem-based learning applied to medicine since 1987. The Université de Sherbrooke was founded fifty years ago and has been known for its innovative pedagogical approaches, including its cooperative system. In 1987, the Sherbrooke Faculty of Medicine shifted from traditional teaching to PBL as a main instructional approach. In the 1990s, many engineering programs (e.g., mechanical engineering, electrical engineering, computer engineering) followed the trend and adopted problem-based and project-based learning as their central approach to teaching.

Systematic faculty development, including compulsory sessions on PBL and on clinical reasoning, is offered on an annual basis to all faculty members in medicine in a life-long learning perspective (Grand'Maison, 1999). Additional workshops and training sessions are available to recently hired professors. The PBL curriculum is regularly reviewed and updated. In 2001, The Sherbrooke Faculty of Medicine became the only World Health Organization Collaborating Center in Canada. Their mandate from that perspective is to consistently develop human resources for public health issues through research and innovative practices.

One of the main difficulties with the PBL approach to teaching is to initiate a transition to or implement some of its applications in an otherwise traditional teaching context where logistical and human resources are limited. The first challenge is conceptual. Both professors and students need to be trained into PBL if an effective shift is to be launched. The development of appropriate problems to structure the learning and the presence of sufficient human resources also constitute potential challenges to this transition.

Implementing PBL in a Traditional Context – Hybrid Models

A number of studies report successful results in either completely shifting from traditional teaching to PBL or in implementing limited and controlled units or modules of PBL within an otherwise traditional curriculum. These latter endeavors served as models on how such transition can realistically be attempted and inspired the intervention that took place in the context of this study.

In all successful implementation of PBL modules or activities within otherwise traditional instructional context, the students and the instructors need to be well informed about the nature of PBL. The students, for instance, need to clearly understand what PBL is about and why and how their role is going to be different from what they are familiar with, if they are accustomed to traditional lectures. How students experience and understand the alignment of the various components of a PBL design has a direct relation with the quality of their learning (Prosser, 2004). Prosser argues that students need to be engaged in thinking about what it means to study in a PBL context compared with a more traditional context. He claims that a good understanding of the PBL mode of instruction is needed for students to adopt deep approaches to learning. When students have insights into the rationale and principles of PBL, although they need time to get acquainted and feel comfortable, they develop positive perceptions about this instructional environment and generally perceive PBL as enhancing their learning (Dochy, Segers, Van den Bossche, & Struyven, 2005).

Another aspect that needs to be clarified for students experiencing group learning for the first time is the specific roles of the students and tutor in such a context. Bennett and Osana (2001) observed that students were otherwise at risk for feeling they were denied the professor's content expertise or that the professor was avoiding having to prepare lecture material.

Similarly, the professors need to engage in a personal review of their own perspectives on teaching and learning. Particularly in contexts where traditional teaching has been used for a long time, professors need to rebuild their personal identity (Savin-Baden, 2001). It is recommended that instructors become familiar with Collins, Brown, and Newman's (1989) model of cognitive apprenticeship and practice its associated teaching methods (i.e., modeling, coaching, and scaffolding). Because cooperative skills are central to group problem-solving in PBL (Peterson, 1997), professors should also develop skills about and become comfortable with leading group discussions without being directive.

One possible option for schools that want to opt for a shift toward PBL but are facing a PBL tutor shortage is to train all students in the same way as the regular instructors (McMaster, 2005). Consequently, when only one tutor/instructor is available per group, including large classes of thirty to a few hundred students, the students can form tutorless and autonomous groups. The role of the single tutor then becomes to monitor and hold the groups accountable for their learning. Such an instructional context has the potential to empower the students but it might also place them at risk for a lack of timely feedback if the students have limited experience with PBL. Parikh, McReelis, and Hodges (2001) noted that the level of peer and group feedback was markedly less in institutions that had recently added PBL to their curriculum as compared to institutions where PBL had been the regular mode of instruction for several years.

In order to ensure a smooth transition to PBL or to accommodate for limited implementation of PBL activities in a well established traditional context, hybrid models of PBL might be a more realistic option. Many institutions have successfully implemented hybrid models (Clark, 2002) of PBL. That is, they maintained lectures in some if not all of their programs and included PBL only in specific study programs, courses or modules, in an effort to take into account their specific social, academic, and cultural contexts (Fink, 2003).

The PBL model at the home institution of the tutor who contributed to this study can be qualified as a hybrid model from the same perspective. Not all programs are problem-based and within the specific programs using PBL, not all courses are problem-based. The first year of the physics program is organized around PBL and students receive specific training in PBL through an orientation program. They use mainly short tutorials to introduce the mathematical skills and the initial body of knowledge in physics. The other courses are problem-based. The problems are sequenced so as to lead the students through the entire curriculum. Typically, the students work in groups of six people and tackle one new "real life problem" per week. A tutor is present to ask questions, guide, facilitate the learning process, and monitor the problem-solving and progress of the students. Among the desirable skills and competencies to be developed by the students, in addition to higher level cognitive skills and problem-solving efficiency, are self-directed learning, critical thinking, group work, facility with oral communication and effective presentation of information. Each group is assessed on a continuous basis and feedback is provided regularly. Self-assessment is introduced about halfway through the first year of the physics program, once the students have become familiar with the evaluation criteria and overall PBL functioning.

The intervention that was designed for the present study does not fit perfectly into any of the already presented models because it constituted only a brief intervention (one week) for which the participants had only a one-hour introduction to the PBL process and functioning. This PBL experience was not integrated into a more global PBL module or PBL course context. It stood alone as a very first contact with PBL for the volunteers who participated in it. Nonetheless, this PBL intervention included all of the typical features that can be expected of a PBL session (i.e., group work to tackle a challenging and ill-defined problem under the supervision of a tutor).

The intervention was designed as an extracurricular activity that did not impact on the regular class time or course grade of the participants. However, the format did match closely the sequencing of activities that the Irish students typically experience during one week at the home institution of the tutor, once they have reached their regular mode of functioning (i.e., one week to complete a problem, two two-hour tutored sessions per week, one scheduled student-only meeting per week, and at least one hour of self-directed study taking place outside of class). Moreover, the students had to clarify and document their learning issues as a part of the PBL problem-solving process. The problem was complex and required that participants build on their prior knowledge along with constructing new knowledge and understanding,

It appears that the lecture and PBL instructional approaches, that were both of particular interest in this study[4], have positive assets in effectively fostering students' learning. No pedagogical method is good in all situations and both have strengths from a physics education perspective. However, because of the deep learning and collaborative skills it helps develop, the PBL approach appears to be particularly beneficial for students' learning. A number of factors are actually likely to contribute to make an instructional environment conducive to the development of students' cognitive skills and problem-solving. A good understanding of the variables related to the learner is one of them and it will be discussed in the next section.

Students' Epistemologies and Approaches to Learning

If we are to assist students in developing stronger cognitive processes and problem-solving abilities, we need to have a better understanding of their views on learning and their perceptions about their role as students in general. It is also important to be able to capture such epistemologies with appropriate instruments.

Epistemologies

The students' traditional perceptions and approaches to learning might need to be transformed. For instance, physics students are not necessarily used to being active participants in their courses. Their expectations and understanding of their role might

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[4] Because no laboratory related to electromagnetism took place during the same semester, this instructional approach could not be included in the design of this study.

very well be reductive, especially when it implies being relatively passive and trying to remember facts and equations. Memorized collections of formulas tend to be dissociated from their physical meaning and do not lead to the development of thinking skills.

Students' perceptions and conceptualizations of their learning and role as students have an impact on what and how they learn (Hammer, 1994; Roth & Roychoudhury, 1994). Students start their first year in university with a range of prior conceptions about their domain and ways to study it (Prosser & Trigwell, 1999). Students' approaches to learning are rooted in their personal experience of learning, based on years of schooling, and informed by the perceived and/or actual culture of the instructional milieu. A number of authors have addressed and categorized students' approaches and learning styles or have developed instruments to measure them. The perspectives have not always been the same. The result is sometimes not illuminating as this literature is full of inconsistent labels and terminologies.

Berlyne (1965), for instance, made a distinction between *reproductive thinking* and *productive thinking*. He described reproductive thinking as an approach where the student applies knowledge to situations very similar to those already encountered. In contrast, he described productive thinking as taking place when the power of creativity leads to generating new mental content. He asserted that it is in this instance that prior knowledge can be modified and reorganized. Students with such an approach to learning are more independent and display more expert-like strategies when solving problems. Reproductive and productive thinking represent two ends of a continuum. Undergraduate students' approaches to learning physics could be anywhere between the two extremities.

Perry (1970) offers another perspective concerning students' approaches to learning. His four stages of intellectual development are characterized by students' perspectives on learning. They range from *dualism*, which is associated with a perception that learning is about accumulating knowledge as provided by teachers or direct observations and with an almost total acceptance of authority, to *commitment*, which is connected with views where learning is a process of constructing one's own understanding and of committing autonomously to some point of view arrived at independently.

In a case study with mechanics students, Hammer (1989) used Perry's (1970) framework and verified that its first and fourth stages accurately reflected and helped describe the two quite opposite approaches to learning observed among his study participants. One strength of Perry's scheme is that, unlike other stage theories, students are not expected, once they reach a specific stage, to remain at that level. As pointed out by Bateman and Donald (1987), it is possible for students to display different stages depending on their area or familiarity with the discipline. This finding is consistent with the literature on expertise which has shown in numerous contexts that expertise is discipline specific. Though some knowledge and abilities can be transferred from one discipline to another, the status of being an expert in a specific domain is not necessarily sustained from one subject area to the next.

From a different angle, Perry's scheme might need to be revisited. Bateman and Donald (1987) tested the construct and empirical validity of Perry's framework with Cégep students. Their results showed that rather than four stages of development, there are two possible levels or general positions that students adopt about knowledge. These are:

1. knowledge consists of facts and data and professors should supply them;
2. knowledge is a quest in which students have responsibility for their own learning, and are expected to be able to judge the validity of arguments and to identify and defend their own point of view (Bateman & Donald, 1987, p. 44).

These results suggest that students who adopt a perspective on learning consistent with the second view identified by Bateman and Donald are more likely to become autonomous thinkers and to actively engage in higher-order thinking processes. This might ultimately lead to more effective problem-solving strategies.

Though Perry's scheme can be another framework to examine students' approaches to learning, it can be argued that there is more than the students' reliance on the professor or their difficulty in challenging accepted ideas that impair some students' ability to become autonomous thinkers and problem-solvers. For instance, students' approaches to learning in physics, including their metacognitive skills and their personal goals when studying are also likely to have an impact on the development of various cognitive processes.

Instruments to Capture Students' Views

Another aspect that could influence students' approach to learning is the demanding workload of physics courses combined with the often highly competitive milieu in which students work.

This might trigger the use of strategies "expected" to lead to fast and successful outcomes instead of the lengthier and more in-depth processes involved in developing thinking skills. This hypothesis is supported by Biggs (1987) perspective on approaches to learning. He defines three main approaches: (a) *surface* – meeting minimal requirements; (b) *deep* – having intrinsic interest in what is being learned; and (c) *achieving* – enhancing ego and self-esteem to obtaining the highest grades (Biggs, 1987). "These profiles represent an individual's *general orientation* to learning: that is, a composite of motivational states and strategy deployment that is relatively consistent over situations" (p.3). Biggs has developed a standardized test to measure these approaches.

Yet another perspective is to relate students' learning strategies to their level of motivation. Paul Pintrich and his colleagues (Pintrich, Smith, Garcia, & McKeachie, 1991) designed a self-report instrument – the Motivated Strategies for Learning Questionnaire (MSLQ) – to assess college students' motivational orientations and the use of different learning strategies in the case of college courses. More specifically, the questionnaire addresses three main themes: motivation, cognitive and metacognitive strategies, as well as resource management strategies. Further studies on learning tend to show the importance to jointly consider the motivational (e.g., students' perception of the classroom environment, personal goals, etc.) and the cognitive components of academic performance (e.g., elaboration, organization, metacognitive strategies, etc.) (Pintrich & Garcia, 1995).

Others have approached students' views from the specific angle of physics. The Maryland Physics Expectations Survey (MPEX) (Redish, Saul, & Steinberg, 1998) claims to assess beliefs that are context-independent among college-level students. This is an interesting asset since most results obtained through instruments of the same type are usually highly dependent on the context that the student has in mind while answering the questionnaire. The very lack of control over such context, and maybe even contexts, chosen or imagined by students when responding, reduces significantly the reliability of many instruments. One criticism raised by Andrew Elby and included in Redish's (2003) accompanying CD documents, highlights the limitations in the validity of the MPEX questionnaire. The MPEX relies exclusively on Likert scale "agree/disagree" items. It becomes almost impossible to prevent the students from getting the impression that there is a right or wrong answer to each item, which invariably leads them to choose what they think they are "supposed" or expected to say.

Another instrument developed specifically for physics is the Epistemological Beliefs Assessment for Physical Science (EBAPS) (White, Elby, Frederiksen, & Schwarz, 1999), though in this case, the intended group is high school students. EBAPS aims at avoiding the polarization (agree/disagree) of the students' answers by including multiple-choice questions, as well as mini-debate items (Elby, 2001), in addition to its MPEX-style agree/disagree items. The mini-debates seem to be an especially interesting technique for triggering critical thinking while revealing the students' epistemological perspectives.

Each of these reviewed categorizations of students' perspectives and approaches to learning and/or instruments has something to contribute to the present study. Some scales are particularly promising, such as Pintrich's subscales on critical thinking or on metacognitive self-regulation. However, these instruments are generally meant to suit a broad range of instructional contexts and disciplines, as well as a large range of age groups which limits their "fit" or level of adaptation to a specific clientele.

Actually, no single instrument addresses the needs of this study exactly. Even the ones that are specific to physics are not appropriate because they are meant for introductory classes. To have used them would have introduced a major limitation in the present context. The electromagnetism courses which constituted the context of this study were for advanced physics undergraduates, students who had already completed at least a year in their respective program and who were still enrolled for a second year of courses. Because in year two, enrolled students are significantly fewer than those in the first year, it is reasonable to assume that the second year ("U2") students in physics are "self-selected" students on their way to completing their degree, and hence have a different cognitive and motivational profile than U1 students. It is also expected that they have a more robust or clearer opinion on what it entails to be a physics student. Their perspectives on physics learning along with their approaches to learning must be influenced by their personal experiences in this field. This special target group called for specific and more tailored instruments.

Inspired by the instruments and scales reviewed above, an instrument was developed for this study to specifically address the perspectives of advanced undergraduate students. Though this instrument could not benefit from the validation that most of the instruments reviewed above can claim to have, items in this questionnaire took into account the reality and specific context of second year physics students when assessing their approaches to learning and conceptions of their role as physics students. The elaboration and initial validation of this instrument will be discussed in detail in the next chapter.

Students' Misconceptions

Another body of literature, derived from the physics education domain, was reviewed to see how it addressed teaching and learning in physics. What stands out in this literature is a discussion on students' conceptual difficulties along with the importance for professors to be aware of them in order to address them specifically in their teaching.

L. C. McDermott (1990, 1991b) and Redish (1994) assert that the student mind is not a blank slate on which new information can be written without regard to what is already there. If the instructor does not make a conscious effort to guide the students into making the modifications needed to incorporate new information correctly, the students may do the rearranging. In that case, the message inscribed on the slate may not be the one the instructor intended to deliver. In fact, beyond the individual difficulties a student may experience, there are some common difficulties that a significant percentage of students encounter in physics. Some of them are sufficiently serious that meaningful learning is precluded.

In this literature, the commonly shared difficulties are referred to as "misconceptions." These are highly resistant to change (Clement, 1982) and conflict with the concepts being taught (Van Heuvelen, 1991). Some may be due to limited experience while others may result from a misinterpretation of previous experiences (L. C. McDermott, 1990, 1991b). Numerous studies demonstrate that students leave their courses in about the same status as they entered, i.e., with the same misconceptions as when they started (Van Heuvelen, 1991). For instance, three studies related to misconceptions (Desautels, 1985; Dickie, 1988; Halloun & Hestenes, 1985) concluded that conventional mechanics instruction has little effect on the student's basic knowledge state. Moreover, Peters' (1982) results show that even honours students exhibit some of the same kinds of misconceptions as do students in standard introductory classes. In fact, Confrey (1990) summarizes the situation in his review by stating that certain constellations of these belief systems (or misconceptions) show remarkable consistency across age, ability, and nationality. This situation of "universality" of misconceptions calls for a reconsideration of traditional instructional strategies in order to foster a deeper level of understanding. The physics education literature has limitations from this last perspective. It offers insights into the specific nature of misconceptions in given sub-domains of physics, suggests instructional strategies to overcome these misconceptions, and formative assessment approaches to help students become aware of their prior conceptions (Dufresne & Gerace, 2004). However, it offers little on the development of the cognitive processes and problem-solving abilities that are requested of physics graduates.

The Professor

Before engaging in any interactions with students or teaching any content to them, the professor brings with him/her personal baggage into the classroom. This includes one or many conceptions of teaching, some pedagogical knowledge and teaching expertise along with innate personality traits. All of these features contribute to defining who the professor is both as an individual and as an instructor in his/her practices. These features are addressed in the next section.

Conception(s) of teaching

Various frameworks exist to describe the range of existing conceptions and views of teaching. Most describe the role of the professor in terms of a continuum (Saroyan, Amundsen, Jazvac, & Bouchard, 2001) going from a "teacher-centered" to a "student-centered" (e.g., Pratt, 1997; Sherman, Armistead, Fowler, Barksdale, & Reif, 1987).

One example is D. Fox's (1983) categorization of the conceptual models that teachers have about teaching into four basic *theories of teaching*:

1. Transfer Theory: knowledge is a commodity to be transferred from one vessel to another;
2. Shaping Theory: teaching is a process of shaping or moulding students to a predetermined pattern;
3. Travelling Theory: subject is a terrain to be explored with hills to be climbed for better view points with the teacher as the travelling companion or expert guide;

4. Growing Theory: focus is more on the intellectual and emotional development of the learner.

This framework presents a set of four theories ranging from a simple theory (e.g., theory 1) to a more developed one (e.g., theory 4) in terms of their respective viewpoints' refinement and complexity and also in terms of the students' level of involvement in their own learning process. D. Fox's (1983) descriptions seem to be depicting relatively static categories or labels that could serve to describe the view of a teacher. In other words, though his theories are ordered in terms of an increasingly active role for the students (i.e., 1: vessel to be poured in; 2: clay to be moulded; 3: traveler to be guided; and 4: emotional and intellectual being), it is not assumed that teachers can progress from one stage to the other. The categories rather describe typical perspectives that some teachers or even departments are more inclined to identify with.

A limitation of D. Fox's (1983) framework thus appears to be the absence of a mechanism for teachers to evolve from one theory to another. His framework is presented as a tool to facilitate the a) acknowledgement of the existence of different perspectives about teaching and learning among faculty members and in various departments, and b) discussions about these perspectives among colleagues and educational leaders.

In contrast, Ramsden's (1992b) theory of teacher growth and Mezirow's (1991) transformative theory about adult education present teaching as a dynamic process that can be improved and which contributes to an individual's personal and professional blooming.

Mezirow, for instance, describes how a change in the basic assumptions of professors about themselves as learners, the goal of education and the role of the teacher can trigger changes in practices among adult learners who are able to examine and acknowledge such a change.

In Samuelowicz and Bain's (1992) framework, too, teacher-centered and learning-centered orientations to teaching and learning can be defined in terms of multiple constituent belief dimensions:

- desired learning outcomes;
- expected use of knowledge;
- responsibility for organizing or transforming knowledge;
- nature of knowledge;
- students' existing conceptions;
- teacher-students interactions;
- control of content;
- students' professional development;
- interest and motivation.

Trigwell, Prosser, and Taylor (1994) used a phenomenographic method to explore intentions and associated strategies of first year science professors. Their results are condensed in an interesting matrix that combines four intentions (i.e., information transmission, concept acquisition, conceptual development and conceptual change) and three strategies (i.e., teacher-focussed, student/teacher interaction, and student-focussed) into five approaches. Given the compatibility of their work with that of Ramsden, it is a bit surprising nonetheless not to find in Trigwell et al.'s (1994) paper any references to Mezirow's or Ramsden's work or to any other piece of research between 1991 and 1994. These years corresponded to a productive and rich period for the advancement of knowledge about conceptions and approaches to teaching. Most of all, this period established the importance of studying the mechanisms through which faculty members evolve as teachers and as individuals.

To embark on a journey toward teacher growth (see Amundsen, Saroyan, & Frankman, 1996), an open mind, self-reflection and the will to modify one's thinking and beliefs are necessary. This is a long and complex process likely to involve a revised approach of evaluation and assessment as well. Based on evidence in the literature (e.g., D. M. Kagan, 1992; Mezirow, 1991; Ramsden, 1992b; M. F. Pajares, 1992), Amundsen et al. (1996) assert that "any real change in teaching practice is preceded by conceptual change in thoughts and beliefs" (p.4). Their subsequent work (e.g., Saroyan, Amundsen, & Cao, 1997) also reached similar conclusions about the possibility for professors to induce a change in their practice after reconsidering and changing consciously the focus of their views on teaching.

From a different perspective, Levander and Repo-Kaarento (2004), based on their practice as faculty developers, suggest that changes in conceptions are easier to achieve and more strongly internalized after a change in practice has been successfully attempted and appreciated for its merit and success with students. Given the robustness of prior literature on the topic, it seems more probable for changes on conceptions to precede changes in practice than the reverse. However, Levander and Repo-Kaarento's (2004) assertion on the stronger internalization of a conception, following its actual experimentation in an authentic context, brings an interesting contribution and suggests that the stability of new or recently embraced conceptions of teaching could be enhanced by successful results in the classroom. This also raises a question and possible trend for research: how resistant would a recently embraced conception be in the face of mitigated or disappointing outcomes in the classroom, even if the new conception initially appeared comfortable and logical from a conceptual and intellectual perspective?

The orientations and conceptions of teaching just reviewed are not all associated with the same degree of potential in fostering the development of cognitive process. Complex cognitive processes are best developed in environments where: a) students are active participants (Hativa, 2000) rather than passive listeners, and b) knowledge is constructed and challenged by the group (McKeachie, 1994) as opposed to being possessed and delivered by a unique source, namely the professor.

A student-centered approach does not correspond to the prevalent model in most physics courses and it certainly does not describe what the current physics professors were exposed to during their own years as students. Traditionally, students in physics are offered a role in which they listen to theoretical lectures given by their professors and take down notes. It appears that the professors' conceptions of teaching and learning in physics are rarely challenged and complemented by compatible conceptions among the physics students (e.g., 'students appreciate well-prepared lectures and demonstrations', Donald, 1994).

As is apparent from these studies, teachers' conceptions of teaching can vary in time and from one individual to another, as a function of multiple factors. From a more general perspective, conceptions of teaching also appear to vary across disciplines. For example, Kreber, Durling, Lazaridou, and Prokop (1999) found that perceptions, about how intellectually stimulating "learning about teaching" is, varied significantly across the eight disciplines they investigated (i.e., mechanical engineering, linguistics, nursing, educational and counselling psychology, physics, sociology, philosophy and the fine arts). In particular, the extent to which this activity (i.e., learning about teaching) involved the development of discipline-specific knowledge also varied significantly from one discipline to the other.

This specificity of each discipline leads to the consideration of another teacher characteristic that can have a determining influence on their approaches and teaching practices: their pedagogical content knowledge (Shulman, 1986).

Pedagogical Content Knowledge

Pedagogical content knowledge was defined by Shulman (1986) as the knowledge which "goes beyond knowledge of subject matter per se to the dimension of subject matter knowledge for teaching" (p. 9). Within this category, he includes features such as the most regularly taught topics in one's subject area, the most useful form of representations, the most powerful analogies, examples, demonstrations, or illustrations, an understanding of students' conceptions and misconceptions along with appropriate strategies to deal with them. Pedagogical content knowledge has also been viewed as a set of special attributes that help someone transfer the knowledge of content to others

(Geddis, 1993). Similarly, Cochran, King, and DeRuiter (1991) differentiated between a teacher and a content specialist in the following manner:

> Teachers differ from biologists, historians, writers, or educational researchers, not necessarily in the quality or quantity of their subject matter knowledge, but in how that knowledge is organized and used. For example, experienced science teachers' knowledge of science is structured from a teaching perspective and is used as a basis for helping students to understand specific concepts. A scientist's knowledge, on the other hand, is structured from a research perspective and is used as a basis for the construction of new knowledge in the field. (p. 5)

A broad pedagogical knowledge and repertoire of instructional strategies is thus a requisite for being an effective and exemplary professors. Some specific training in teaching cognitive skills might be necessary to gain comfort and confidence in using approaches such as *inquiry* (Hammer, 1995, 1997; L. C. McDermott, Shaffer, & Constantinou, 2000) or *problem based learning (PBL)* (Kolmos & Krogh, 2003a, 2003b). Particularly in the context of physics teaching, a good understanding of students' specific preconceptions, prior knowledge, and misconceptions, including the most common ones among students (see Clement, 1982; Confrey, 1990; Dickie, 1988; Driver, Guesne, & Tiberghien, 1985; Goldberg & McDermott, 1987; Halloun & Hestenes, 1985; Hammer, 1994; L. C. McDermott, 1991a; L. C. McDermott, Rosenquist, & van Zee, 1987; Reiner, Slotta, Chi, & Resnick, 2000; Rosenquist & McDermott, 1987; Peters, 1982; Ryan & Aikenhead, 1992) is a highly desirable asset.

An in-depth comprehension of what is a good lecture is crucial (see Saroyan, 2000) since physics professor often have to teach large groups. Hake (1987), L. C. McDermott, (1991a), Schauble (1996), and Van Heuvelen (1991) also offer a good review of the specific components of lectures in physics. Other instructional approaches for teaching physics should be considered and understood [e.g., cooperative and interactive learning (Burron, James, & Ambrosio, 1993]; cognitive conflict (Chinn & Brewer, 1993); microcomputer-based laboratories (Hewson, 1985; Monaghan, Goldberg, Otero, & Johnson, 1999); and Socratic Dialog Inducing (Hake, 1987)). The mastery of a rich repertoire of instructional methods as they can be applied for physics teaching allows for more variety and adaptation to the changing needs of students and constitutes sound pedagogical content knowledge.

Shulman's approach to teachers' knowledge "led to a shift in understanding and a new valuing of teachers' work" (Loughran, Mulhall, & Berry, 2004, p.371). Of course, the subject matter content knowledge (Shulman, 1986), which is related to the concepts and principles of a discipline, their organization, and the methods used to validate this knowledge, is also an essential component of the various types of knowledge that need to be mastered by a teacher. This knowledge has not been developed here because this content expertise is more or less assumed among physics professors. However, just like the *pedagogical content* knowledge, which was reviewed in this section, *pedagogical* knowledge often constitutes a challenging mission for faculty who are rarely trained formally in pedagogy prior to their academic careers. In order to address this issue, the defining characteristics of expertise in teaching are discussed in the next section.

Teaching Expertise

Being an expert in a specific domain is itself an accomplishment. However, it does not necessarily correlate positively with expert teaching in the same domain. Furthermore, even years of experience as a practitioner will not guarantee expertise in teaching. Berliner (1986) refers to this as the "confounding of experience and expertise." Teaching is a particularly complex and ill-defined task and mastering it is quite challenging. In defining the work of the faculty members in terms of four categories (e.g., Teaching, Research and creative activity, Practice and professional service, and Citizenship), Braskamp and Ory (1994) note the complexity of what teaching entails which includes instructing, advising and supervising students, developing learning activities, and developing as a teacher.

An expert pedagogue in higher education can, among other things, explain educational goals, understand the institutional context, understand students, provide a disciplinary context and a learning community, and establish student responsibility for learning, all of that in order to assist students to develop intellectually (Donald, 2000). Expert teachers also have developed metacognitive and self-regulatory skills. They are capable of "reflection-in-action" (Schön, 1987): they can monitor and evaluate non-verbal as well as verbal student cues while instructing and are flexible enough to modify their approaches and actions accordingly (McAlpine, Weston, Beauchamp, Wiseman, & Beauchamp, 1999). Leinhardt and Greeno (1986) refer to this ability as "visual scanning" of the classroom. Experts have knowledge about the self and the capacity to reflect on one's practice [see Schön (1987) for the concept of *reflective practice*] which help practitioners to grow. Experts can selectively encode, combine, and compare information to arrive at insightful solutions (depth of problem representation) to teaching problems (Sternberg & Horvath, 1995). They also have strategic judgement and display "wisdom of practice" (Shulman, 1986).

With the development of technology, a new category of competencies can be added to the already long list of outstanding features shared by expert teachers: being an exemplary computer-using teacher able to encourage the effective use of computers among students (Becker, 2000). Consequently, a developmental conception of teaching appears reasonable to make possible the transition towards excellence in teaching (Sherman et al., 1987).

Personal Traits

Unlike problem-solving that one can practice alone, or even chess where the interaction with the opponent is minimal, teaching is a social interaction between human beings. The quality of this relationship is greatly affected by the personalities of the actors. It appears that some personality traits also tend to be shared by expert teachers. The presence of these traits in a particular individual does not necessarily result in expertise but these desirable personality traits have been addressed in the literature on excellence in teaching. An important body of research within the teacher effectiveness literature describes studies looking into identifying characteristics, factors, personality traits, and classroom behaviours that students associate with teachers' effectiveness and recognize as such by giving them high ratings when evaluating instruction (Young & Shaw, 1999).

As introduced by Lavely et al. (1986), some desirable traits of an effective teacher are: communication ability, interest in students, encouraging classroom participation, stimulation of interest, friendliness, and fairness. Hativa (2000) discusses the importance of other traits such as promoting student attention and keeping them alert by one's enthusiasm and dynamism, incorporating anecdotes to pace the sessions and raise student interest, analogies to add clarity and foster transfer, using self-disclosure to provide a personal context to the topic and connect with students, or maintaining eye contact with students, etc. The importance of diversity in the lecturing style was also stressed by Saroyan and Snell (1997) and Saroyan (2000).

Berliner (1986) presents the expert teacher as someone who changes track quickly while the inexperienced teacher tends to be disturbed when something unexpected forces him/her to make last minute modifications to their plan. Again, a developmental perspective is appropriate. Personal traits might appear more innate or stable within an individual than conceptions. However, being aware of the traits that can best facilitate the establishment of a positive and effective communication with students is an asset and a first step in the intentional choice to develop as many of them as possible.

Young & Shaw (1999) identified six features that were rated the highest by students evaluating global teacher's effectiveness and accounted for 87% of the variance:

1. the value of the course;
2. motivating students to do their best;
3. comfortable learning atmosphere;
4. course organization;
5. effective communication;
6. concern for students' learning.

It can be noted that among these most significant features, #2, #3, #5, and #6 are directly related to personality. This contributes to establish the importance of the professors' personality traits in the students' learning experience.

Though the features most appreciated by students are not necessarily grounded in sound instructional principles, they nonetheless reveal the factors that contribute to students' comfort in a learning context where an instructor is in charge, which corresponds to most of the teaching situations that university students are exposed to. Moreover, the validity of students' ratings has been studied extensively and is supported in numerous studies (e.g., Marsh & Bailey, 1993) and reviews of the domain (e.g., Greenwald, 1997). It is interesting to note that students' preferences can vary depending on the level of their studies. For instance, Murray, Rushton, and Paunonen (1990) found that traits such as sociability, changeableness, liberalism or extraversion showed non-significant negative correlations with teacher effectiveness among graduate students in their study while these same traits displayed positive and significant correlations with teacher effectiveness among undergraduates.

Now that various factors contributing to the development of cognitive processes and problem-solving abilities have been reviewed, the assessment of such competencies is going to be discussed in the next section.

Investigating Problem-solving Abilities

One cannot directly observe the mediating cognitive processes (Ericsson & Smith, 1991) involved in problem representation. This is why controlled problem-solving tasks are among the most popular tools for researchers interested in cognitive science.

To capture the essence of problem-solvers' reasoning, various strategies can be considered. One of them is the non-intrusive and direct observation of a "quiet" solver in action but this reveals limited information. Another approach consists of the utilization of verbal protocols which has repeatedly proved fruitful in the analysis of complex processes

(Taylor, 1966). Experts and novices alike can be asked to think aloud as they solve problems in order to provide as detailed as possible a description of their every thought and decision related to the problem-solving activity. Audio and video recording of the episodes form the basis for analyzing the cognitive processes involved.

As reported in Larkin et al. (1980), observations are, in ideal conditions, obtained once every half-second. The human cognitive processes are actually much faster (within a few tens or hundreds of milliseconds). This is an important limit of such a methodology, not to mention the lack of awareness of some of the participants about their own thought mechanisms. This situation substantially limits their ability to report accurately the sequence of operations as they solve a problem. The mastery of the language or of the appropriate vocabulary to describe one's thoughts might represent an issue as well. That is why Taylor (1966) strongly recommended that thinking aloud protocol data be used as sources of hypotheses concerning process and that such hypotheses be subject to rigorous tests. "One method of rigorous testing is through simulation – through the expression of a computer program and the comparison of the behaviour of the program with that of human subjects (p. 125)"[5].

Another criticism about think aloud protocols is that giving verbalizations can in some cases interfere with the concurrent cognitive processes and change the performance and consequently the results (Hutchinson, 1985). Also, many types of expertise cannot be captured realistically by a set of reproducible "laboratory" tasks. Nonetheless, verbal protocols still are potentially extremely rich sources of data. Through introspection, they attempt to make visible internal processes that would otherwise remain hidden to the observer.

A developmental perspective of the study of problem-solving is brought forward by Glaser, Lesgold, and Lajoie (1988) who emphasized the need to understand how expertise is acquired and how it can be taught. Research involving expert tutors

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[5] One immediately sees that such a kind of systematic testing is virtually impossible when dealing with ill-defined tasks such as teaching.

interacting with novices, including various levels of scaffolding from clarification to hints and instruction, to actual demonstration (e.g., Frederiksen & Donin, 1999) are consistent with that perspective and also address the need for cognitively valid assessments of students' cognitive processes in coached, collaborative, and problem-based contexts as discussed by Snow and Lohman (1993).

The discourse processes body of literature has made available systematic approaches to capture manifestations of complex processes and skills and study interactions. For instance, Frederiksen and Donin (1999) and Frederiksen (2005) in a retrospective on their engineering tutoring studies demonstrate how some discourse analysis tools can be used to monitor (Frederiksen & Breuleux, 1989) and analyze the discourse (Frederiksen, Bracewell, Breuleux, & Renaud, 1990) and problem-solving actions of a tutor during a problem-solving session with a small number of students.

These studies provide a framework for the systematic analysis of video data from tutored sessions. They inspired this study's approach for looking into a) the nature of the interventions made by an expert physics tutor leading a problem-based intervention, and b) interactions among the students as they were solving a challenging problem. The conversation analysis for the study of reasoning in groups discussed in Glenn, Koschman, and Conlee (1999) and specific techniques for verbal analysis, elaborated by Chi (1997), were complementary and relevant approaches to explain students' collaborative problem-solving in the context of a problem-based learning activity.

Summary

Five bodies of literature were reviewed in the context of this study. Each had a specific and unique contribution. The expertise literature, for instance, was very informative on what an expert physicist is and does. However, the very process of developing such expertise in problem-solving, including how to proceed from a novice stage (i.e., student) toward an expert level (i.e., professor), appears to be a missing piece from a science teaching perspective.

The cognitive science literature provided insight on students' thinking and cognitive abilities as well as on indicators that can help capture them. These fed directly into the third research question.

Research on protocol and discourse analysis proved particularly informative from a methodological perspective while documenting how to best assess problem-solving skills or the nature of students' interactions with a tutor. This literature inspired the fourth research question.

The physics education literature shed light on teaching and learning in physics with a particularly abundant body of findings pertaining to students' misconceptions. While this literature provided hints for professors who are interested in helping their students overcome these known difficulties, a gap appears to remain in terms of concrete opportunities to develop the problem-solving abilities and cognitive skills that students need to develop.

The literature on students' approaches helped document the ways in which students' perspectives can be captured and interpreted which inspired the first research question. One conclusion about this literature is that little is available to address the specific situation of advanced undergraduates, especially in the electricity and magnetism domain. This situation suggested the design of a tailored instrument.

Finally, the instructional psychology literature was reviewed to document effective instructional practices susceptible to foster students' development of cognitive and problem-solving skills. It appeared that the traditional lecture-based instruction and the problem-based learning approaches both had very positive assets to offer and they consequently became the object of the second research question.

In the light of the literature reviewed, the following four research questions were articulated to structure the study.

Research Questions

Question 1. What are the approaches to learning of undergraduate physics students and what are their general perceptions about their role as physics students?

Question 2. How is instruction of electromagnetism characterized when taught in the traditional format and using the PBL approach? To what extent are metacognition, critical thinking, physical intuition, and general problem-solving processes modeled by the instructors, in each of these settings?

Question 3. To what extent do physics students display evidence of metacognition, critical thinking, physical intuition, and general problem-solving abilities when they solve advanced electromagnetism problems?

Question 4. What are the cognitive actions, processes, and activities that students engage in while learning to solve problems in a PBL environment?

CHAPTER 3 – METHODOLOGY

Setting

This study took place at a Canadian Research 1 University. This university attracts top students from over 140 countries. The overall average entering grade of first-year students is 89%, one of the highest in Canada. It has a total of about 32,000 students, 22,000 of whom are undergraduates.

This university offers over 340 programs in twenty-one (21) schools and faculties. Many fields of study are available to students interested in science. At the undergraduate level, international students and those coming from other Canadian provinces who have not completed equivalent courses to those offered in Québec Cégeps are typically admitted in the Freshman program in science. This program is a prerequisite before the regular program in science, whether it is physics, chemistry, mathematics, etc.

Students who have successfully completed a Cégep science program in Québec are admitted as U1 students in a 3-year undergraduate program of science. During the subsequent years, they will be designated as U2 and U3 students (according to their year in their respective programs). For those specifically interested in the field of physics, the undergraduate curriculum offers diversified options and programs.

The Physics Programs

Among the possible choices, the two main programs of physics are of particular interest to this study. These are the major and the honours programs in physics. The *Major Program in Physics* consists of sixty (60) credits.

> [It] offers a broad training in classical and modern physics and yet leaves room for the student to take a meaningful sequence of courses in other areas. It is intended primarily for students who wish to pursue careers in fields for which physics provides a basis. However this program also provides a preparation for graduate studies. (University X, 2003)

The *Honours Program in Physics* is meant for students who are particularly strong in mathematics and physics and who are looking for a thorough preparation for graduate work and an academic or professional career in physics. The program often includes supervised research and typically involves a higher degree of specialization than the major program. The courses are particularly demanding. Honours students are required to maintain a GPA of at least 3.00 out of 4.00, throughout their course of study.

The Advanced Electromagnetism Courses

Regardless of whether they are students in the major or the honours program, undergraduates in physics have two advanced courses of electromagnetism in their program. The first one is a prerequisite for the second. Both "Electricity and Magnetism" and "Electromagnetic Waves" are offered during the fall and the winter semesters of the "U2" year for the physics major students. Honours students have the equivalent of the same two courses "Electromagnetism" and "Electromagnetic Waves" although in this case, the courses are distributed respectively over the "U2" and the "U3" years of their program. The sequence of the courses is presented in Table 2.

Table 2
The Advanced Electromagnetism Courses

	U2		U3	
Program	Fall	Winter	Fall	Winter
Major	Electricity and Magnetism	Electromagnetic Waves		
Honours	Electromagnetism		Electromagnetic Waves	

Each course carries a weight of three (3) credits. The first course of advanced electromagnetism (whether it is the major or the honours version) addresses the fundamental laws of electric and magnetic fields and typically covers similar content and concepts, including methods for solving problems. The topics addressed in both the major and the honours versions of the second course, related to electromagnetic waves, are also similar and include: Maxwell's equations, vector and scalar potentials, electromagnetic waves, reflection, refraction, polarization, transmission lines and waveguides, dipole and quadrupole radiation. The honours courses are assumed to be more demanding and thorough than their major counterparts.

Design

A within-stage mixed-model design (Johnson & Onwuegbuzie, 2004) was used in this study to address the four research questions. Data on students' perspectives, instructional contexts and teaching, as well as on learning and the means by which that learning was generated and supported (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003) were collected via the coordination of various data sources.

To address the first question, concerning the approaches to learning of undergraduate physics students and their general perceptions about their role as physics students, the study made use of a survey developed especially for that purpose (described in detail in a forthcoming section).

To address the second research question, regarding the characterization of instruction of advanced electromagnetism when taught in the traditional format and using the PBL approach, different data sources were used. For the traditional format context, extensive field notes and observation grids were used during classroom observations of the habitual teaching of the regular instructor. For the PBL context, a small group of volunteers participated in a special series of PBL activities led by an expert tutor over a period of one week. The PBL sessions constituted extracurricular activities for these students who also attended their regular advanced electromagnetism classes as usual. These sessions were videotaped. The degree to which each context offered explicit modelling of specific cognitive processes (i.e., metacognition, critical thinking, and physical intuition) and problem-solving abilities to advanced undergraduate students was also documented. The interviews conducted with the two instructors complemented the instructional data.

To address the third question, concerning metacognition, critical thinking, physical intuition, and general problem-solving abilities of advanced undergraduate students when solving familiar and unfamiliar electromagnetism problems, two problem sets were especially designed to collect evidence of the presence or absence of a number of indicators for each of these cognitive abilities and processes. The first problem set served as a pre-test and was presented to all of the participants before the PBL intervention. This PBL intervention dealt with concepts not yet addressed in class. Consequently, the second problem-set (post-test) was administered immediately after the PBL intervention (yet before similar content was addressed in class) for the students who had participated in the PBL activities. After similar concepts and notions had been studied in class, the same post-test was then administered to the students who had remained in the traditional context. The different dates for the administration of the post-test for the two subgroups of students (PBL and non-PBL) meant to isolate the effect of each instructional context the students had been exposed to.

This aspect of the research corresponded to a multivariate repeated measures with control group design (Campbell & Stanley, 1966). There was one between-subject factor i.e., treatment (traditional instruction vs. PBL) and one within-subject factor (pre- vs. post-test). The teaching in the traditional instruction group was unaltered. Therefore this traditional instruction group could serve as a control group. The PBL special session constituted the treatment for a subset of the students.

To address the fourth question, regarding the cognitive actions, processes, and activities that students engage in while learning to solve problems in a PBL environment, the video-recording of the PBL sessions was used. The nature of the tutor's interventions as well as the students' interactions among themselves were also investigated. This aspect of the study constituted a case study.

Participants and Sampling

The study was carried out in two phases. Survey data were collected during the first phase (Fall 2003 semester). All of the other aspects of the data collection (i.e., classroom observations, PBL intervention, pre- and post-tests, and interviews) took place during the second phase (Winter 2004 semester).

Two cohorts of students (major and honours) were approached for the first phase of the study while one cohort was invited to participate in the second phase. The solicitation method to reach the participants is presented below.

The participating students of these various cohorts constituted the three samples of the study; each sample was related to one or two specific research questions. Table 3 (page 68) summarizes the association between the four research questions and the three samples of students. The three samples are described in the following sections.

Participants in the Phase I of the Study

For the first phase of the study, two cohorts of students (n_{TOT}=66) attending second-year courses on electromagnetism were invited to fill in a survey during the Fall 2003 semester.

Solicitation of Participants for Phase I

A written invitation (see Appendix A) to participate in Phase I of the study was sent to the students of the two cohorts (major and honours) through the respective professor of each group during the Fall 2003 semester. The invitation was sent two weeks prior to the date that each professor and the researcher had agreed upon for the administration of the survey. It provided information about the purpose and context of the study and the expected roles of the participants. Both professors had accepted to provide the researcher with one hour of class time to meet with the students, answer their questions about the study, and administer the survey.

Sample A: Traditional Teaching – Fall 2003 Semester

Each cohort [major (n_{maj}=41), honours (n_{hon}=25)] was taught its respective course of advanced electromagnetism (Electricity and Magnetism or Electromagnetism) by a specific professor. Each course was a unique instructional context, as different from the other one as the two professors teaching them. The possible differences in these instructional contexts do not invalidate the "quasi-comparability" (Campbell & Stanley, 1966; Cook & Campbell, 1979) that can reasonably be expected of contiguous cohorts. The curriculum for both cohorts is very similar in nature. In theory, the two cohorts of students have also been exposed to similar training before attending their electromagnetism courses.

No *a priori* hypothesis was generated about potential differences between the students of these two cohorts regarding the nature of their answers to the survey. However, to control that time and maturation alone were not responsible for potential differences in the measurements – as well as to supplement the analysis of the results – the very nature of the instructional contexts, culture of the milieus, and specific curriculum to which each cohort had been exposed to was documented. Potential differences between the two cohorts were explored in this light. Among the possible sixty-six (66) students in total of these two cohorts of students, fifty-one (51) filled in the survey. They constituted the "Sample A: Traditional Teaching – Fall 2003" and their answers to the survey formed the body of data that most contributed to answering the first research question.

Participants in Phase II of the Study

For the second phase of the study, one cohort (n_{TOT}=41) of major students attending a more advanced second-year course on electromagnetism, "Electromagnetic Waves," was invited to participate in the research during the winter 2004 semester.

Solicitation of Participants for Phase II

A written invitation (see Appendix B) to participate in Phase II of the study was presented to the potential participants by the researcher at the end of a regular class of "Electromagnetic Waves" in early February 2004. Their professor had provided the researcher with a fifteen-minute time slot to present the invitation, explain the study and answer any questions the students might have. Thirty-four students (out of a possible maximum of forty-one) were present in class on that day.

There were two types of activities that the students were invited to participate in during the winter 2004 semester: the problem-solving assessments (a pre- and a post-test) and the special problem-based learning (PBL) activity to take place sometime between the two assessments. Each of the problem-solving assessments was going to last approximately 50 minutes and consisted of 2 electromagnetism problem-solving exercises to be completed during regular class time provided by their professor. The special PBL activity, however, needed to take place outside of the regular class schedule and specifically during the week of March 22nd to March 26th, 2004 – given the scheduled stay of the physics PBL expert visiting from Ireland.

This in-class initial invitation was made six (6) weeks prior to the date on which the PBL activity was going to begin. The letter provided information about the purpose and context of the study, the expected roles of the participants as well as the benefits they could expect from their participation. The researcher entertained the questions of the students. The students were also invited to provide the days and time slots that best suited their individual schedule, should they choose to participate in the PBL activity.

Sample B: Traditional Teaching – Winter 2004 Semester

The professor teaching the course "Electromagnetic Waves" to this cohort was one of the two professors who had participated in Phase I. The normal teaching of this professor constituted the *traditional instruction* or natural setting for the participating students.

There were forty-one students ($N_{TOT}=41$) in this cohort. Nineteen (19) students completed the first set of problem-solving exercises (pre-test) and fourteen (14) completed the post-test. It did not turn out to be possible to use only regular class time for the two problem-solving assessments and this could have contributed to the actual number of students willing to participate in the data collection for both the pre- and post-test. Pooled together, these thirty-three (19+14=33) different problem sets were collected from twenty-one (21) different individuals. These twenty-one (21) individuals composed Sample B and data generated by them contributed to answering the second and third research questions.

Sample C: PBL – Winter 2004

Twenty-two (22) of the thirty-four students present on the day of the invitation expressed interest in participating in the PBL activity and provided information about their available time slots during the week of March 22nd to March 26th, 2004. The information collected from the students was compiled and guided the drafting of a schedule that would accommodate as many potential participants as possible, while meeting the requirements and sequencing of the specific activities designed jointly with the PBL expert.

After consulting with the guest PBL expert via e-mail, a final schedule was laid out and the students were contacted. An individual e-mail (see Appendix C) was sent to each of the twenty-two students who had expressed an interest in participating. The e-mail presented the details of the PBL activities to take place as well as the benefits that they could expect. The e-mail also acknowledged the level of fit between the proposed PBL schedule and the student's own availability. When appropriate, the possible adjustments to the schedule were explained. All of these twenty-two students replied to the e-mail invitation. Among them, sixteen said they would likely participate to the PBL activity. Eight (8) of these students subsequently signed a consent form specific to the PBL activity. In the end, four (4) students actually committed themselves to all of the PBL related activities as planned. These four (4) students constituted Sample C.

The *PBL intervention* or treatment was consequently offered to this small group[6] of volunteers[7], self-selected within the same cohort. The PBL activities were led by a guest PBL expert tutor and dealt with a topic not yet addressed in their regular class at the time of the intervention. These special PBL activities, limited to Sample C, took place outside of the regular class time and required the participants to dedicate over twelve hours of their time.

The remaining portion of the cohort (i.e., the students not participating in the PBL special activities) consequently composed the "Control Group" or "Traditional Teaching Group" (Sample B) described above. The students in Sample B remained at all times in their natural setting, attending only their regular "Electromagnetic Waves" classes, taught by their regular instructor.

Thus, there were two samples considered for the second phase of the study. Sample C: PBL group ($n_{PBL}= 4$) was composed of the individuals who accepted to participate in Phase II by committing to all PBL activities AND to completing both the pre- and the post tests. Sample B, i.e., the control group (Traditional Teaching Group, $n_{TRAD}= 21$) was composed of the twenty-one (21) individuals out of the remaining thirty-seven of the same cohort who accepted to participate in Phase II by completing either or both the pre- and post-test, without ever being exposed to the PBL activities. Table 3 summarizes the association between the research questions, the samples and the data sources. The data sources and their associated instruments are described in the next section.

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[6] The PBL participants were not expected to be familiar with (or even to know anything about) the PBL approach of teaching. Consequently, it was agreed beforehand with the PBL expert tutor that no more than two teams of four to six students each (Donham, Schmieg, & Allen, 2001) would be constituted in order to offer a learning context as conducive as possible to a productive experience of PBL. Moreover, a relatively small number of PBL participants was also meant to allow the PBL tutor to provide as close a supervision as needed.

[7] Because of the particularly time consuming nature of the designed PBL activities and the need for the participants to commit to all of them over a one-week period of time, the students had to be volunteers (as opposed to randomly assigned participants).

Table 3

Research Questions, Associated Sample(s), and Data Sources

Research Question	Sample(s) & Conditions	Data Source(s)
Question 1: What are the approaches to learning of undergraduate physics students and what are their general perceptions about their role as physics students?	A: Traditional Teaching – Fall 2003 (n=51)	Survey
Question 2: How is instruction of electromagnetism characterized when taught in the traditional format and using the PBL approach? To what extent are metacognition, critical thinking, physical intuition, and general problems-solving processes modeled by the instructors, in each of these settings?	B: Traditional Teaching – Winter 2004 (n=21) + any other students of the cohort attending class[8] C: PBL– Winter 2004 (n=4)	• Observation Grids & Field Notes • Video-recording of PBL Sessions • Semi-structured Interviews with both Instructors
Question 3: To what extent do physics students display evidence of metacognition, critical thinking, physical intuition, and general problems-solving abilities when they solve advanced electromagnetism problems?	B: Traditional Teaching – Winter 2004 (n=21) C: PBL– Winter 2004 (n=4)	Electromagnetism Problem Sets (students' notebooks)
Question 4: What are the cognitive actions, processes, and activities that students engage in while learning to solve problems in a PBL environment?	C: PBL– Winter 2004 (n=4)	• Video-recording of PBL Sessions • Students' Flip-chart Sheets (developed during their PBL team work)

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[8] Note: When observing classes to document the instructional context, no distinction was made between the students in terms of whether they were participating in the study or not. For that specific aspect of the data collection, all students were equal.

Instrumentation and Data Sources

Five main data sources were used in this study: (a) a survey, (b) electromagnetism problem sets, (c) an observation grid to help document the instructional settings, (d) a video-recording of the PBL intervention, and (e) semi-structured interviews with the instructors. Table 3, presented previously, includes a summary of the associations between the four research questions and the five bodies of data which are described below.

Survey

Inspired partly by the instruments and scales reviewed in the previous chapter, a questionnaire was developed for this study: *Approaches to Physics Learning and Conceptions of One's Role as a Physics Student* (APL/CORPS). The APL/CORPS was tailored to assess the perspectives of advanced undergraduate physics students. The details of its elaboration and validation are presented in this section.

Elaboration of the APL/CORPS

There were four main dimensions in this questionnaire; they pertained to the students' (a) personal experience of their current physics program, (b) academic experience of their current physics program, (c) perspectives on physics learning, and (d) perceived role and participation in the classroom, as physics students.

A blend of formats was used for the items: multiple choice, Likert-type scales, short-answer items, as well as open items. Some mini-debates, similar in construction to the ones used in "Epistemological Beliefs Assessment for the Physical Science – EBAPS" (White et al., 1999), were also included. While the EBAPS is meant for a middle school audience, the participants in the present study were young adults who were assumed to be able to articulate their personal opinions. Consequently, in addition to the four or five different choices of responses, typically provided to the students to summarize their personal position on the divergent stances presented in a debate format of the EBAPS, the researcher allowed the students to phrase their own opinion themselves if they wished to do so or if the proposed choices did not match their views.

The items related to metacognitive skills and critical thinking were adapted from Pintrich et al. (1991). Finally, in order to supplement the students' profiles, additional information was also collected regarding age, gender, spoken and written language(s), high school or Cégep GRA, background education and location, etc.

The preliminary version of the APL/CORPS contained eighty-four (84) items, including ten (10) demographical questions, twelve (12) questions on the students' personal experience of their program, twenty-nine (29) questions on their academic experience, twenty-five (25) questions on their perspective of physics learning, and eight (8) questions tapping into their role and participation in the classroom as physics students.

Validation and Revision of the APL/CORPS

A face and content validation of this preliminary version of the survey was conducted with a group of five (5) graduate students in physics. An electronic invitation to become a reviewer was sent to a group of graduate students in physics. It provided a brief description of what their participation in the study would entail (see Appendix D). The consent form for the graduate student reviewers is presented in the Appendix E. They were asked to draw on their experience as physics students to judge and rate, on a Likert scale of 1 to 4, the clarity (1- not clear at all to 4- very clear) and the relevance (1- not relevant at all to 4- very relevant) of each item. *Clarity* referred to how easy the item was to understand for an undergraduate student in physics. The reviewers' age and level of advancement in their masters program were judged to be representative of those of advanced undergraduates. Their proficiency in English was also important to ensure that they were good judges of the wording and meaning of the items and questions. In addition to their written comments, the reviewers were asked to describe their interpretations of the items verbally. R*elevance* pertained to how connected and pertinent the item was to the category and dimension it belonged to. For the purpose of the validation, the items were organized by dimensions and categories and included instructions for the reviewers.

The graduate students were encouraged to provide suggestions and comments on how to improve the wording of the items at the end of each category. Potential modifications were discussed immediately to ensure that a common understanding was reached. An excerpt of the tool that was used with the graduate students to validate the preliminary version of the APL/CORPS is presented in the Appendix F.

In the light of the numerical answers, written suggestions, and comments of the five graduate student reviewers, a revised version of the APL/CORPS was prepared. The decision to maintain, modify, or remove one item altogether was based on the following guidelines:

1. An item was removed if either a) at least 2 reviewers found the item not clear[9] OR b) at least 2 reviewers found the item not relevant[10].
2. An item was revised and rephrased if a) at least one reviewer found the item unclear[9] or not relevant[10] AND provided specific comments on his/her rationale for this rating. The item was then rephrased in the light of the comments or suggestion(s) of the reviewer(s).

An example extracted from the decision matrix that led to the selection and occasional rephrasing of the initial items of the APL/CORPS (leading to a second version of the instrument) is presented in the Appendix G. The categories of topics addressed within each dimension of this second version of the questionnaire, along with the number of items for each, are presented in the Appendix H. This second version is the one that was administered to participants (Appendix I).

Problem sets

Two problem sets were designed specifically for this study. They were used in the pre- and post-test respectively. The details of their elaboration, construction and validation are provided in the following section.

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[9] An item was labelled "unclear" when a graduate student reviewer rated it "1 (not clear at all)" or "2 (somewhat unclear)" on a Likert scale of one to four.

[10] An item was labelled "not relevant" when a graduate student reviewer rated it "1 (not relevant at all)" or "2 (somewhat irrelevant)" on a Likert scale of one to four.

Elaboration of the Problem Sets

Three categories of cognitive processes were of particular interest in this research. As presented before, these were metacognitive skills, critical thinking, and physical intuition. Problem-solving related abilities were also central to this study. Rather than attempting to measure them directly, manifestations or indicators of these cognitive processes and abilities were collected via especially designed problem-solving exercises. The actual problem-solving activities and artifacts were used as an important body of data for this research. The description of the various indicators measured is presented below. The construction and the structure of the problem sets follow.

Description of the Measured Indicators

Metacognitive skills.

In light of the reviewed body of literature, three competencies were selected and assessed in this study within the context of especially designed electromagnetism problems (in both the pre- and post-test) to evaluate students' metacognitive skills:

- planning skills for a specific problem and detailed justification of the proposed steps (Royer, Cisero, & Carlo, 1993);
- application of the plan as well as readjustment and modification of the plan when necessary (Pellegrino et al., 2001);
- accuracy of the student's level of confidence (Phelps, Graham, & Kerr, 2004) in the exactness of his/her plan as well as solution.

The students were asked to lay out both a solution plan and an executed plan when solving specific electromagnetism problems. Moreover, the students were asked to state their level of confidence in their plan and actual solution.

These measures were meant to assist in obtaining rich and meaningful data as opposed to plain answers to the problems. All problem plans, drafts, graphs, calculations, intermediate steps, tentative versions, and actual solutions were done in a notebook provided to the participating students in order to keep track of every element of writing and any possible evidence of their self-monitoring. These metacognitive considerations also constituted the rationale behind the various levels of difficulty that were intentionally included in the problem sets. This range of difficulties offered an opportunity to see the potential adaptation and readjustments of the students' problem-solving strategies as a function of the difficulty of the problem.

Critical thinking.

To appraise students' *critical thinking*, three indicators were considered:

- the student's discriminating ability, which is the capacity to differentiate between relevant and irrelevant data in word problems (Beyer, 1997);
- the student's ability to categorize problems, on the basis of the problem's surface and deep structure (Chi et al., 1981; Mestre et al., 1993; Van Heuvelen, 1991);
- the student's ability to estimate a realistic range of answers; a reasonable forecast (Wright, 2001) which will lead to critically evaluate the logical consistency and accuracy of the final solution (Beyer, 1997).

Before actually solving a problem, the students were asked to estimate a realistic range of answers to the problem at hand and to justify why their forecast made sense. They were asked to specify the units they were using for their predictions.

The students were also required to categorize the problem on the basis of its deep structure and surface features. For the deep structure features, a listing of about fifteen laws (e.g., Ampère's Law), equations (e,g., Maxwell's equations), and principles (e.g., energy is conserved) was provided and the students were invited to select as many as applied. They were told they could add any item they perceived to be missing if needed. For the surface features, a listing of over thirty elements was provided (e.g., dielectric, magnetic fields, waveguide, etc.). The students could select any of these if they thought them to be involved in the problem at hand. Again, they could select as many as needed and were free to add any missing item if they wanted to.

Physical intuition.

Physical intuition is a subtle asset, nonetheless an essential component of expertise in physics (Singh, 2002). It can be stimulated through advanced and unfamiliar problems where students cannot rely on their current and familiar content knowledge. In each problem set, one problem was based on unfamiliar content. This was meant to reveal three possible indicators of the students' physical intuition:

- the ability to predict (Lavoie, 1993) or anticipate possible trends or alternatives to solve the problem, even if it pertains to an unfamiliar content;
- the ability to clearly identify the gap in their knowledge, and/or missing information from the given statement of the problem [i.e., what is not known that may be important (Thompson, 1995)] and might prevent them from solving the problem;
- the ability to generate analogies or to find links between the unfamiliar situation or phenomena and a more familiar one. Such problems call for student creativity and predictive abilities. Self-generated analogies, developed when facing a novel situation, allow students to move "beyond the boundaries of concrete memorized facts, into the conceptual gray area where understanding is tenuous and incomplete" (Wong, 1993, p. 368).

The students were asked to elaborate on the possible options or steps they could take to solve a particularly challenging problem. They were not required to attempt solving the problem (though they could if they wanted to) but only to explain how they would proceed if they were asked to.

In addition, they were prompted to identify gaps in their knowledge and/or missing information in the problem statement that they would need in order to solve the problem satisfactorily. In an attempt to trigger the students' physical intuition, they were also asked whether the problem at hand seemed analogous to another situation or problem context they had already encountered. They were invited to describe similarities between this problem and a more familiar one and to generate analogies.

The global intention was to see how the students would go about solving a difficult (or advanced) problem for which they clearly lacked some knowledge. This approach corresponded with the notion that "[w]hen asked to deal with novel situations, the specific cognitive skills and learning strategies we have available become more critical than the limited content knowledge we may possess" (Ertmer & Newby, 1996, p.7).

Problem-solving abilities.

The measure of problem-solving ability was arrived at by using indicators that, unlike the indicators just reviewed, were not explicitly asked for in the statement of the problems. These were expected to appear "naturally" as they are indicators of some aspects of students' proficiency as problem-solvers and include:

- the students' ability to accurately recognise and acknowledge any relevant assumptions that should be made in the particular context of the problem (Dottin & Weiner, 2001);
- their ability to translate or represent the problem into a graphical form, a sketch, or a pictorial representation (Van Heuvelen, 1991);
- their ability to translate verbal or written statements into the language of mathematics (Larkin et al., 1980) and to develop an accurate physical representation of the problem (Maloney, 1994);
- the overall quality, completeness, and accuracy of their solution including possible evidence of multiple trial-and-error attempts (Hayes, 1989) and evaluation of alternative solutions.

Thus, the students were not explicitly asked to produce a graphical representation or to write down any specific equation. However, each problem necessitated working with equations that the students were expected to write down and manipulate at one point or another of their solution. The students' choice of equation(s) and ability to use them correctly when solving problems constituted important information which was used to assess the quality and accuracy of their solution. From the same perspective, the problems all naturally led to drawing a sketch or a graph. The presence (or absence), the nature, and the relevance of any graphical representation provided insight on the students' understanding of the concepts involved in a specific problem. Students' sketches in general also shed light on the students' personal strategies and global approach to problem-solving.

Construction and structure of the problem sets

The two problem sets integrated all of the different indicators just reviewed. They were used respectively as a pre-test and a post-test with both the traditional teaching participants (Sample B) and the PBL participants (Sample C).

Though the post-test addressed topics different from those of the pre-test, the structure of these two sets (pre- and post-test) was similar. The reasons for the different topics being addressed in the pre- and post-test were twofold: (a) to avoid contamination from the pre-test and (b) to acknowledge the "more advanced" state the students were at in their course.

The content and topic of each set of problems were tailored for the level the students were at in their program at the time of the assessment. Within each set, there was one problem addressing content knowledge that was already familiar (prior knowledge) to the students at the time of administration and one problem addressing material not yet covered and therefore unfamiliar to the students. The target completion time of each set of problems was between forty-five (45) and sixty (60) minutes. Each set was constructed according to the following structure:

Problem 1.

The first problem of each set included both elements of a relatively low level of difficulty (addressing a content familiar to the students) as well as elements of moderate complexity, yet still linked to a familiar content matter. This first problem was especially designed to tap the three indicators of metacognitive skills already presented as well as the three indicators of critical thinking.

More specifically, the problem prompted the students to initially draw a detailed plan of their solution-to-be along with a justification of every step. Students also had to include in their plan a realistic forecast of a possible range of answers along with a critical justification for the "credibility" of their forecast. This approximation of the expected solution was meant to assist them when assessing their results later on in the process. When it was impossible for them to solve the problem completely and/or successfully, this expected range of values replaced the missing and final answer in their retrospective evaluation.

As they solved the problem, if students wanted to readjust or modify their plan, they had to document these changes and to express their level of confidence about the exactness of their plan and obtained solution. Supplemental or irrelevant data were purposely included in the statement of the problem. Finally, the students were asked to categorize the problem on the basis of its deep structure (i.e., laws, fundamental equations, and principles it pertained to) and surface features (i.e., main topics and elements related to the problem such as a dielectric or a magnetic field). A number of options were proposed to them for each category and they were free to generate their own answers if they wanted to.

Considering how unfamiliar this whole approach to problem-solving probably was (i.e., writing down a plan) and the relative constraints it imposed on them (e.g., justifying every step), in the pre-test, the students were presented with a choice of two problems in lieu of #1 (1.1. or 1.2) and asked to answer only one of them. The two problems were equivalent in terms of their complexity but different in terms of the specific topics they addressed.

The rationale for offering the students a choice was twofold: (a) allow the students to select a problem – and its constituents – that they felt comfortable with and (b) provide an opportunity for the students to best demonstrate their cognitive processes and problem-solving abilities, despite the novelty of the approach to problem-solving that was required of them. No such choice was offered in the post test. There was one problem #1 and one problem #2 in the post-test, and the solving of both was mandatory.

Problem 2.

The last problem of each set (pre- and post-test) tapped into content knowledge not yet addressed in the course in order to trigger the use of students' physical intuition and to lead them to transfer acquired knowledge and cognitive abilities to novel situations. The three indicators of physical intuition discussed previously were investigated through this problem.

The students were not expected to solve this second problem. They could solve the problem if they felt up to the challenge. The record of activities showed that some attempted to solve the problem and were clearly on the right track. The primary goal was to prompt the students to elaborate on the potential trends that a successful solution would take, if they had undertaken the process. From the same perspective, they were invited to identify the gap(s) in their knowledge and/or the nature of the missing information that they would have required to successfully and completely solve this difficult problem. Finally, the students were asked to generate at least one and possibly many analogies with a more familiar situation that could somehow be linked to the problem at hand.

All the attempts, intermediate steps, sketches as well as mathematical proofs and complete or incomplete solutions were collected as evidence for capturing the students' problem space (Newell & Simon, 1972). The written pieces produced by students when attempting to solve a problem set (either for the pre- or the post-test) provided elements of the students' external representations and ultimately insights about their internal representations.

The plans the students drew shed light on their goals and sub-goals for each of the problems. The occasional absence of a plan or the inability to successfully detail and justify one's planning constituted in itself valuable data in the context of this study. The structure of the answers also helped document the methods used by the students to search for a solution, such as trial and error, proximity methods, fractionation methods and knowledge-based methods (Hayes, 1989).

Validation of the Problem Sets

The five graduate students who had reviewed the survey were contacted again to assess the face and content validity of the problem set templates. In other words, they were not presented with the actual problems as the specific topics addressed might have distracted them from judging the characteristics and the wording chosen to describe the tasks required of the participants; rather, the reviewers were presented with the skeleton of the problems. The role of the graduate student reviewers consisted in appraising the nature and clarity of the instructions and questions intended for the participants who were undergraduate students. Their role did not require them to judge the appropriateness of the physics related content-knowledge addressed in the problems. As graduate students in physics, they were not assumed to be knowledgeable about the level of difficulty and nature of the specific curriculum dealt with in an undergraduate course such as "Electromagnetic Waves".

The reviewers were provided with background information about the cognitive processes and problem-solving abilities to be assessed in these problems. They were asked to rate the relevance and clarity of each item of the templates on a Likert scale of one to four. They were also prompted for comments and suggestions about the choice of words for the items and related instructions. An excerpt of the tool that was used with the graduate students to validate the problem set templates is presented in the Appendix J.

In a similar fashion to what had been done for the validation of the survey, the numerical answers and the comments of the graduate students were tallied. None of the problems or sub-questions was judged unclear or irrelevant and hence nothing was removed in the light of this assessment. However, the wording of some sub-questions was revised based on their suggestions in order to render the expressions clearer.

The specific content knowledge was then added into the templates and thus the real problems were created. The problem statements were inspired by the exercises presented in various electromagnetism textbooks (e.g., Cheng, 1989; Grant & Phillips, 2003; Halliday & Resnick, 1965; Marion & Heald, 1980; Redish, 2003) and also by the advanced electromagnetism teaching materials available from various physics departments in North America (e.g., University of Maryland, University of Washington, etc.) that the researcher had reviewed. This approach ensured that no problem would come directly from (or even resemble one from) a textbook that the students had potential access to. Another important aspect taken into consideration was not to interfere in any way with or compromise the professor's teaching and evaluation in the course. Consequently, the problem statements used in exercises or exams over the previous years in the same department were neither selected nor adapted for this study. In addition, the researcher made a point of not designing problems that would resemble the exercises and exam problems to be used by the professor during the winter 2004 semester. These materials, the course syllabus provided by the professor, and the researcher's field notes from classroom observations helped situate as precisely as possible the level the students could be expected to be at during different periods in the semester. This knowledge was essential in designing problems that would be appropriate for the specific weeks of data collection.

The professor was presented with a draft of the problem sets to obtain advance approval. The professor assessed the match between the level of the students and the difficulty of the problems and he validated the wording of the problems designed for the pre- and the post test as well as the accuracy of the concepts and principles they involved. A revised and final version of the problem sets for both the pre-test (Appendix K) and post-test (Appendix L) was prepared in light of this feedback.

Problem-based Learning Problem

This section presents the elaboration and validation steps taken to develop the PBL problem used in the PBL intervention for this study. When using a PBL approach, the problem is the starting point to the students' learning process and serves as an anchor at all times during subsequent related activities. In the context of this particular study, the PBL intervention was meant to provide an opportunity to capture the processes that students engage in while learning to solve problems in a PBL environment.

Elaboration of the PBL Problem

Similarly to the development of problem sets for the pre- and post-test, the problem used for the PBL intervention had to be carefully designed, taking into account the level the students were going to be at, at the time of the intervention. In the case of the PBL problem, this condition was even more subtle and crucial since the problem had to be slightly more advanced than the level of the students at the time of the intervention. This was necessary in order to induce in them a real need so they would want to go further and to discover new grounds. Nonetheless, it had to be within their reach, involving topics and concepts that they were about to approach, at least partly, in their regular classes. Solving this problem satisfactorily also had to be an achievable mission over the one-week period during which the PBL activities were going to take place.

Again, the course syllabus, the researcher's observations of the classroom, and numerous discussions with the professor teaching the Electromagnetic Waves course proved useful to precisely identify the level that could be expected of the students at the time of the PBL intervention. It was a determining first step to be achieved since a good PBL problem is based on a careful analysis of students' current content knowledge (Weiss, 2003).

It was also important to get a solid grasp of the fundamental features and desirable characteristics of good PBL problems. A crucial aspect of any problem-based activity is the actual design of the problem to be solved (Jonassen, 2000). Over a series of e-mail exchanges, the researcher discussed her understanding, mainly grounded in her one-month apprenticeship at the UNESCO Centre for PBL (UCPBL) of Aalborg University[11] and extensive readings on the topic, with the guest expert tutor in physics who was going to lead the PBL intervention in this study. He provided numerous insights and various samples of good physics PBL problems (mostly related to mechanics) to illustrate the essential characteristics. A number of references specifically addressing the writing and the design of effective PBL problems also provided a framework.

Some of the core characteristics of robust PBL problems include:

- be designed to serve as the basis for the learning process (Allen, Duch, Groh, Watson, & White, 2003; De Graaf & Kolmos, 2003)
- be designed to meet specific educational objectives (De Graaf & Kolmos, 2003) and enhance and promote the goals of a course (Weiss, 2003)
- be based on real-life problems (van Kampen, Banahan, Kelly, McLoughlin, & O'Leary, 2004) and/or rooted in real world situations (Allen et al., 2003)
- be linked to the students' existing knowledge (van Kampen et al., 2004) and nonetheless also connected to new knowledge (Duch, 1996)
- be challenging and complex enough to require cooperation among the students (Duch, 2001)
- be engaging and stimulating (aligned with the students' interests) (Duch, 2001)

With these characteristics in mind, an original problem related to the design of specific components of a microwave oven was drafted and tailored to meet the special needs of astronauts of the International Space Station. Though most students were likely to have used a microwave oven to heat and cook food before, it turned out to be a good guess that they did not know much about its actual functioning and security features.

One of the goals of the PBL problem was to foster the development of a good conceptual understanding of the physics behind a familiar appliance relying on microwaves to heat and cook food. The students had not yet begun to address waveguides from a theoretical perspective in class but they had basic notions on transmission lines. Another goal of the problem was to help students become more comfortable with concrete applications and detailed calculations, including the impact of the use of

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[11] Aalborg University (Aalborg, Denmark) is an institution entirely organized around problem- and project-based learning. In addition, research on PBL teaching and learning is a part of their mission.

dielectric materials. In addition, the notions of shielding addressed in the problem were clearly more advanced than what the course was going to deal with. They meant to lead the students into documenting and understanding the security features of a microwave oven, questioning existing beliefs and misconceptions about microwave ovens, and even to discover fun facts and useful tips about them. The problem was purposely ill-defined and contained only limited information and a number of constraints. The actual problem statement (or scenario) used for the PBL intervention is presented in Appendix M.

Validation of the Content and Format of the PBL Problem

The draft PBL problem prepared by the researcher was initially revised by the regular professor to ensure its level of difficulty was reasonable for the students. Subsequently, with the help of the PBL expert tutor, the scenario was fine tuned and minor revisions were made to make it meet the criteria and requirements for a robust PBL problem as closely as possible. A detailed solution was also submitted to both instructors. They assessed the solution and both approved it without any modification. This model solution later on became the basis for the problem frame coding scheme that will be discussed in the section on the analysis of the video data of the PBL intervention.

Observation Grid

In order to establish whether the development of cognitive processes and problem-solving abilities were fostered in the course on “Electromagnetic Waves” and to document and describe the nature of this traditional teaching context, a detailed observation grid was developed to help systematize classroom observations.

A specific session was the unit of analysis. For each class of “Electromagnetic Waves” attended, the classroom lectures were examined to determine the:

- content and topics addressed;
- classroom and departmental contexts;
- teaching approaches used by the professor;
- conceptions of physics learning supported / challenged by the course;

- students' involvement, participation / collaboration, peer interactions;
- cognitive processes (including metacognitive skills, critical thinking, and physical intuition) and problem-solving abilities that were modeled, scaffolded, fostered, and/or rewarded in the course;
- cognitive processes and problem-solving which students actually engaged in.

The specific items of the grid were adapted from (D. M. Kagan, 1990) *Configuration Checklist for evaluating a teaching performance.* Her original observational instrument includes thirty (30) instructional features, specific to conceptual change teaching in science, grouped into six main categories (i.e., lesson segments, content, teacher role, student role, activities/materials, and management). Based on the classroom observations, various features could be rated with a 3- or 4-point ordinal rating scale, ranging from *low* to *high* in terms of its implementation. Some additional elements about the use of examples, schemas, analogies, questions and feedback, humor, explicit link to prior knowledge and modeling were also documented. The tool used to collect such information was inspired by the "Grille d'observation sur les techniques d'enseignement" (Cabral, Viau, Bédard, Bouchard, & Dubeau, 1997). The observation grid utilized in this study is presented in the Appendix N.

Interviews

Experiential data were collected through audio-taped semi-structured interviews with the two instructors (professor and tutor) participating in the study during the winter 2004 semester. These interviews constitute the fifth body of data in this study.

Following the framework provided by Samuelowicz and Bain (2001), the interview protocol included general questions on educational issues, views on teaching and learning, students' and professors' perceived respective roles, and indicators of learning. These general themes served as a means to situate and clarify the personal definitions the instructors held regarding various educational concepts. The process proved pertinent in establishing common grounds in terms of vocabulary and terminology to ensure a productive interview.

The interview protocol clearly focused on the instructors' specific conceptualization of physics teaching and learning as well as on their perceptions of their students' cognitive processes and problem-solving abilities. The nature and meaning of these concepts were addressed as a part of the interview. When possible, the researcher tried to touch upon whether the professors intentionally and/or explicitly modeled these cognitive abilities or not, as well as their teaching goals and desired student outcomes. The interview guide (see Appendix O) had been provided beforehand to the instructors to maximize their level of comfort toward the questions and topics discussed in the interview.

Procedure

The study was carried out during the Fall 2003 and the Winter 2004 semesters and consisted of two main phases. In the first phase, the students from two different cohorts (major and honours, $n_{TOT}=66$) were invited to fill the APL/CORPS survey. For the second phase, one cohort of major students ($n_{TOT}=41$) was invited to participate. The data collection was organized around the PBL activities. This intervention was preceded by a pre-test and followed by a post-test. The sequencing of the various data collection activities undertaken in each phase of the study is presented below in Table 4.

Phase I Data Collection

As can be seen in Table 4, data collection for Phase I took place mid-October during the Fall 2003 semester. The *Approaches to Physics Learning and Conceptions of One's Role as a Physics Student* (APL/CORPS) survey was completed in class and took about forty-five minutes to fill. The consent form for the survey is presented in the Appendix P.

Table 4

Sequencing of the Various Data Collection Procedures

Phase of the Study	Step	Date
Phase I (Fall 2003 Semester) ➢ Involving two cohorts (major, honours) of students (Sample A, n=51).	APL/CORPS survey (a questionnaire on students' approaches to physics learning and conceptions of role as a physics student).	October 14th, 2003
Phase II (Winter 2004 Semester) ➢ Involving one cohort of major stduents divided into two sub-samples: the traditional instruction students (sample B, n=21) and the PBL students (sample C, n=4).	a. the pre-test (same problem set for Sample B & C);	March 19th, 2004
	b. the PBL intervention involving a PBL expert tutor (for PBL students only: Sample C);	March 22nd to 26th, 2004
	c. the post-test (problem set) for PBL students only (Sample C);	March 26th, 2004
	d. the traditional instruction (normal and unaltered teaching by the participating instructor);	March 29th to April 5th, 2004
	e. the traditional teaching students' post-test (same post-test as for the PBL students, but administered at a different time, Sample B).	April 6th, 2004

Phase II Data Collection

During the Winter 2004 semester, data collection activities for Phase II had to be carefully coordinated around the PBL intervention considering that the PBL expert tutor was an invited guest from Europe. Accordingly, the PBL intervention and its constitutive activities took place during the week of March 22nd to March 26th. The pre- and post-tests were administered respectively before and after the PBL related activities.

Pre-test

The pre-test was administered on the Friday immediately before the PBL week, i.e., on March 19th. Problem-solving abilities of both the traditional teaching group (sample B) and PBL group (sample C) were assessed through the same set of electromagnetism problems (pre-test). The students were allowed to use their class notes and textbooks as well as calculators to tackle the problems of the pre-test. The researcher made available to students additional copies of the textbook as well as calculators in case someone needed them. The researcher circulated in the classroom during this assessment and was available for clarification questions at all times, should students have expressed any needs in that regard. A total of nineteen participants took the pre-test. On average, these students required between 50 and 60 minutes to complete the task. (See Appendix Q for the students' pre-test consent form).

The following week's activities pertained to PBL learning and involved only the four PBL participants (sample C) and the PBL expert tutor.

PBL Expert Tutor

At his home institution in Ireland, the PBL expert tutor of this study is a learning development officer at his institution's teaching and learning centre. In this capacity, he coordinates the PBL training for academic staff in all areas. He teaches problem-based learning to faculty members using a problem-based learning approach to do so and regularly runs workshops on how to use PBL, both inside and outside his institution. He had initiated the shift from traditional lecture-based to PBL teaching in the physics department of his institution a few years ago. A number of programs are now offered in a PBL format at his home institution while others remain based on more traditional instructional approaches. He also teaches physics at the undergraduate level using PBL as his regular instructional approach.

His participation in this study included collaborating on the design and logistics of the specific PBL activities offered to the participants, contributing to the development of the PBL problem that would be at the core of the PBL sessions, providing resource documents about PBL and presenting an introductory interactive lecture on PBL and tutorial process to the participants, as well as leading two PBL sessions with the PBL participants, both focused on solving the PBL problem.

PBL Intervention

The PBL Intervention consisted of four mandatory activities distributed over a period of one week and taking place outside of the regular class time of the students: a) an interactive lecture introducing the PBL and Tutorial Process, led by the expert tutor, b) a first PBL session to work on the PBL problem, led by the PBL expert tutor, c) a student meeting to continue working on the PBL problem, for students only, and d) a second PBL session to complete the solution to the PBL problem, led by the PBL expert tutor. In addition, students were also expected to dedicate a total of at least two hours on their own (self-directed study). The schedule of the PBL week is presented in Appendix R.

The interactive lecture on the PBL and tutorial process introduced the four participating students to the history and instructional principles behind PBL, clarified the roles of the different participants in PBL sessions, and presented a systematic way to organize group work and functioning during such sessions. Following this session, the students used both tutored sessions as well as their student-only meeting to tackle and solve the PBL problem that had been given to them. The problem involved the design of some components of a microwave oven to be used in the International Space Station. Notions about waveguides and dielectrics (not yet seen in class) and shielding (not to be addressed at all in their Electromagnetic Waves class) as well as basic properties and functioning of microwave ovens were central to the problem. The group was responsible for researching and documenting any gap in knowledge or missing information in the problem statement in order to successfully solve the problem at hand.

The two PBL sessions were video-taped which allowed for the subsequent transcription and analysis of the interactions between the tutor and the students during the tutored PBL sessions. The researcher operated the camera herself from a distance in order to minimize as much as possible the potential discomfort for the students, and to have a good angle on their work space including all of their movements and use of the board.

The researcher did not obtain the authorization to record the student meeting but she attended it to ensure that students were on task and also to collect all the products of their team work. This process is similar to an authentic PBL context where the tutor does not control how many times or for how long students meet among themselves or if they communicate with each other using the telephone or e-mails, for instance, to advance their work in-between the tutored sessions. In the context of this study, the focus was on the nature of the tutor's interventions and interactions with students during the tutored PBL sessions.

At the end of their PBL week, on Friday, March 26th, the four PBL participants were presented with the post-test. As was the case for the pre-test, they were allowed to use their class notes, textbooks, and calculators. On average, they took sixty (60) minutes to complete the post-test.

Traditional Instruction

The PBL students were eventually introduced to some of the concepts (dealt with initially in the PBL Intervention) for a second time in their regular class, once they joined their peers who had remained in the traditional teaching group. As such, their due access to the integral teaching of their professor was not jeopardized. It is important to note, however, that the PBL students' post-test which had taken place immediately after the PBL intervention occurred before any similar concepts were addressed in class. Consequently, the traditional instruction that subsequently followed their participation in the PBL activities did not have any impact on their post-test performance.

The PBL students never missed any regular class because of their participation in the study. The traditional instruction sessions addressing waveguides (as well as many other class periods during the same semester) were observed and documented to objectively and accurately describe the current situation of physics teaching in the advanced courses of electromagnetism.

The classes attended by the researcher were not video-taped since no authorization was obtained from the professor. It has to be acknowledged that it would have been particularly difficult to video-tape in this classroom without being intrusive, given the physical arrangement of the classroom. Extensive field notes were collected with the help of observation grids for thirteen (13) complete class periods over the semester. Consequently, it can be claimed that the description of the traditional setting is representative and closely matching reality.

Post Test

As soon as concepts similar to those involved in the PBL Intervention had been taught in the traditional instruction context, including notions about waveguides and dielectrics, the students of the traditional group were given the same post-test received previously by their peers from the PBL group. The time and day was coordinated with the professor as this post-test assessment took place immediately after a regular class period. Similarly to the PBL students, the traditional students required about sixty (60) minutes to complete the post-test. They could use their class notes, textbooks, and calculators. The researcher made available additional copies of the textbook and calculators for students who might not have brought theirs in class. (See Appendix S for the post-test consent form.)

Interviews

The instructors were interviewed at their earliest convenience during the winter 2004 semester to discuss their conceptions of physics teaching and learning along with their perspectives on students' cognitive processes and problem-solving abilities. The two instructors, the traditional instruction professor and the PBL tutor, were met individually for one semi-structured interview. Similarly to the approach used by Donald (1993), the professors were advised not to feel limited by the questions but to keep one course as a focal point for the interview. The interviews took between sixty to seventy-five minutes. The professor's and tutor's respective consent forms are presented in Appendix T and Appendix U.

Ethical Considerations

As mentioned previously, as a result of the PBL intervention, the students in this group were taught some of the concepts twice, the second time in the company of their peers in their traditional instructional setting. This strategy guaranteed that the students could not be penalized by the experiment in any way.

Moreover, the complete solutions to the problems of the pre- and post-test designed in the context of this study were distributed to all participants shortly after the data collection was completed, a week before their final exam of "Electromagnetic Waves". The PBL students also received the "model" solution to the PBL problem they had encountered regardless of the fact that they had successfully solved it in the context of the PBL activities.

Data Analysis

The analysis of the five bodies of data in this study was facilitated by the use of statistical and qualitative data analysis packages. More specifically, the SPSS statistical package (version 13) was used to obtain descriptive statistics and to perform procedures such as principal components and reliability analyses. The SAS 9.1.3 statistical package was utilized to perform multivariate analyses of variance as well as log-linear analyses. The software package NVivo (version 2.0) was used in analyzing the data of a qualitative nature such as the interview and the video transcripts. Since each body of data called for specific treatments, the presentation of the various analyses performed is organized around the different data sets.

APL/CORPS Survey

This survey had been tailored to match the specific needs of this study and, although it was partly inspired by other existing instruments and scales, it also contained a number of original items never tested before. The development of any questionnaire is an iterative process of construction, assessment, and revision. The face and content validation (discussed previously in this chapter) led to a revised version of the survey (see Appendix I for the second version) which was administered to the participants. As recommended by Spector (1992), in the case of summated rating scales (such as the Likert scales used it the APL/CORPS), it was important to also conduct an experimental validation of the items to verify the robustness of the instrument. The following sections present a description of the procedures undertaken for that purpose.

The first aspects of the experimental validation consisted of a) a Principal Component analysis to clarify the latent variables or dimensions underlying the observed variables/items and b) a Reliability analysis to assess the internal consistency of the instrument and its scales. Once reliable scales had been established, the survey results could be reported on and discussed with confidence. These results led to answering the first research question about the participants' approaches to learning and perceived roles as physics students. The related emerging traits and dominant perspectives are discussed in Chapter 4.

Before launching any analysis with the entered data, some initial preparation of the raw scores (see Appendix V) was necessary to ensure the quality and smooth unfolding of the analysis procedures.

Recoding of the Variables

The first step in preparing the data for analysis consisted in making certain that all of the variables under study were in the same direction. In other words, when a question was formulated in a negative fashion, a low score on such an item actually meant a high score on the construct being measured. For instance, an item such as "I have problems with taking organized notes in physics" (answered on a 5-point Likert scale where '1' corresponded to "Never or Rarely" and '5' referred to "Almost Always") assessed the systematized and structured approach of the student. However, because of the phrasing of the item, a high score on this item actually indicated a limited degree of systematization and structure. The recoding of such variables in the opposite direction was performed to avoid any confusion in the subsequent interpretations of the results. Moreover, although such an adjustment in direction would not have caused any major difficulties during the Principal Components analysis, the Reliability procedure would have been affected, and could have resulted in negative Cronbach alphas, rendering the results virtually impossible to interpret.

Standardization of the Variables

A second step in preparation for the different analyses consisted of standardizing the data to accommodate for the different scales (4-point, 5-point, and 7-point Likert scales) being used in the survey. The Principal Components analysis once again does not require the variables to be standardized beforehand. This is actually built into the procedure. However, standardization is required for the Reliability analysis. Each variable was converted to a standard score (Z-score) by subtracting the mean and dividing it by the standard deviation for each variable. This treatment on the raw data also subsequently allowed for the combination of the summated scales that belonged together and facilitated their conceptual interpretation.

Principal Components Analysis

With the principal components analysis, the goal was to obtain clean composite scales emerging from the measured variables. The survey had been constructed around a number of *a priori* dimensions or themes, presented earlier in this chapter. However, the consistency of these themes and related items had not been tested before in such a survey format and were not grounded in a theory in order to be tested. This implied that a confirmatory factor analysis would not have been appropriate at this point in time. Rather, the intention was to see whether the expected or *a priori* dimensions would actually be corroborated, at least to some extent, by a principal components analysis.

A principal components analysis also opened the door to some emerging variables or components, underlying the observed variables/items, that had not been articulated explicitly in the questionnaire or that were even unsuspected (Rummel, 1970) but that could turn out to best describe the body of data collected with the survey. This aspect was particularly important in the context of the first research question that aimed at identifying the students' characteristic approaches to learning and perceptions about roles as students.

Possibly the most familiar advice regarding the number of cases is to obtain the maximum sample size possible (Rummel, 1970). However, in a real research context, it is not always possible to achieve large sample sizes. In the current study, there were fifty-one students who filled the survey.

The most popular rules suggest that the sample size be determined as a function of the number of variables. For instance, Gorusch (1983), Hatcher (1994), and Bryant and Yarnold (1995) all suggest a subjects-to-variables ratio of at least five. Nunally (1978) goes as far as to recommend a subjects-to-variable of ten (10). However, Guadagnoli and Velicer (1988) argue that virtually none of these subjects-to-variables rules are empirically based. They used a Monte Carlo procedure to systematically vary sample size, number of variables, number of components and components saturation in order to examine the conditions under which a factor solution becomes stable. Guadagnoli and Velicer (1988) results indicated that, contrary to common expectation, sample size as a function of the number of variables was not an important element in determining the stability of a factor solution. The component saturation (i.e., the loadings[12]) and the absolute sample size were the most important conditions. The number of variables per component came next by contributing to a lesser degree. In this study, fifty-one (51) variables from the survey had Likert scales and qualified to enter the initial principal components analysis.

In their recommendations to applied researchers, Guadagnoli and Velicer (1988) concluded that when a component or a scale possesses four or more variables with loadings above .60, it may be interpreted confidently regardless of the sample size. In a

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[12] A loading represents the correlation or linear association between a variable and the latent factor (Stevens, 1996).

study also varying the sample size, number of variables and number of components (but using real data) Barrett and Kline (1981) determined that the minimum sample to obtain and reproduce a stable factor solution was an N of fifty (50). The minimum number of observations recommended by SAS/STAT (1995) is also fifty (50). In a similar yet more comprehensive research than Guadagnoli and Velicer, Osborne and Costello (2004) warned researchers against the possibly simplistic and too rigid rules made of absolute sample sizes, though they praised Guadagoli and Velicer's work for their rigor. They also raised concern about studies that recommended specific subjects-to-variables ratios arguing that they were not empirically supported and that no ratio was likely to work in all cases.

The effect on the study was the following. With fifty-one participants in the survey, the current study is close to the threshold (N=50) suggested by some. This implied that the researcher would have to remain vigilant for the presence of outliers that would potentially cause instability in the results. Despite these limitations, the results reported in the next sections show that it was possible to obtain relatively robust components leading to meaningful interpretations.

The Varimax rotation was chosen as the rotation method since it provided a solution of orthogonal (or uncorrelated) components or scales. It is easier to interpret uncorrelated scales because each item of the final pattern solution loads significantly on one and only one scale i.e., a simple component structure (Dunteman, 1989). No constraint on the number of scales was initially imposed. Initial results were carefully examined and subsequent iterations were conducted until a stable solution was obtained.

The number of scales.

The number of scales to be retained for the final component solution was determined with the help of two different methods. The first method, the criterion of Kaiser (1960), is one of the most widely used (Stevens, 1996) especially when the number of variables remains moderate and the communalities high (ideally greater than

0.70). It consists in retaining only those components that have eigenvalues greater than one (1). The Kaiser (1960) criterion led to start with an initial fifteen-component solution explaining 80.651% of the total variance. Appendix W presents the percentage of variance associated with all components along with their cumulative percentages while Table 5, below, displays only the first fifteen components that constituted the initial solution.

Table 5

Fifteen First Eigenvalues and Explained Variance in the Initial Principal Components Analysis

Component	Initial Eigenvalues		
	Total	% of Variance	Cumulative %
1	6.673	13.084	13.084
2	6.013	11.790	24.874
3	3.795	7.441	32.315
4	3.475	6.813	39.128
5	2.964	5.813	44.940
6	2.625	5.148	50.088
7	2.374	4.654	54.742
8	2.240	4.392	59.134
9	2.079	4.077	63.211
10	1.899	3.723	66.934
11	1.626	3.188	70.122
12	1.578	3.095	73.217
13	1.445	2.833	76.050
14	1.196	2.346	78.396
15	1.150	2.255	80.651

A second method to select the appropriate number of scales is also frequently used in the social sciences (Dunteman, 1989) and is derived from the interpretation of a graphic called the Scree Test (Cattell, 1966) which plots the components (scales) as the X axis and the corresponding eigenvalues as the Y axis.

The Scree Test also suggested retaining a fifteen-component solution. Cattell's rule (Cattell, 1966) is to keep all scales prior to where the plot levels off. As can be seen in *Figure 3* an elbow of the eigenvalues' curve corresponds to the 16th component. This implies retaining the first fifteen items in the solution.

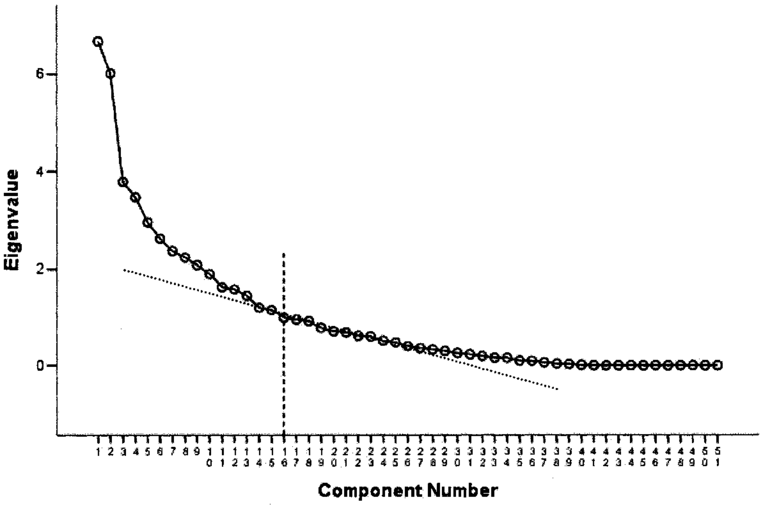

Figure 3. Initial Solution Scree Plot

Since the Varimax rotation was selected, the next step consisted of examining the rotated component matrix containing the scales and the respective loading of each item on them.

Over a number of iterations, some items were removed from the analysis. An item was removed from a subsequent analysis when either of the two following conditions was met:

a) the item did not load significantly on any scale. A rule of thumb or guideline frequently used is that component loadings greater than .30 in absolute value are considered significant (SAS/STAT, 1995). A higher loading cut-off of .4 (in absolute value) was used in this study for a loading to qualify as "significant." Any loading less than .4 (in absolute value) was considered weak and not displayed in the component matrix, in order to facilitate the detailed examination of the results. The items (or observed variables) that did not display any significant loadings on any components were then removed from the subsequent iterations.
b) the item loaded equally and significantly on two or more scales (split loadings).

Table 6 lists the four items that were deleted after the first analysis, either because of non-significant loadings on any scale or because of split loadings.

Table 6
Items Deleted Following the Initial Principal Components Analysis

A Priori Category	Item Code	Item Position in Survey
Study & Homework	2B1	69
Study & Homework	2B5	27
Prep. For Exams	2C4	54
Physics in their Lives	3E5	62

Following deletion, the principal components analysis procedure was performed again. Numerous iterations were conducted in order to refine the solution. Iterations also served the purpose of obtaining the most robust solution possible, i.e., a solution that:

- presented scales that were as clean and interpretable as possible;
- had high communalities (percentage of variance in a given variable explained by all the components jointly) for all of the items remaining in the final solution;
- reduced the number of undesirable doublets and singlets (Thurstone, 1931) since they reduce the factorial validity (Bryant, 2000);
- explained as much of the variance as possible in the set of variables, ideally 75%.

Based on some other minor inflexions (or elbows) in the Scree Plot (see Figure 3), suggesting that other solutions with fewer scales could also be admissible, a number of constrained-component solutions with ten, twelve, thirteen, and fourteen components were attempted. For each trial, the loadings' significance and distribution were examined and the unsatisfactory items were deleted from subsequent iterations. During these iterations, in order to improve the solution, each time an item was deleted, the complete principal components analysis procedure was rerun to evaluate the adequacy of the new scale solution. The resulting amount of variance explained by these various attempts, along with the number of doublets and singlets they each implied, were contrasted in search for the best solution possible given the data set.

A series of more than fifteen tentative solutions with a number of items ranging from thirty-five (35) to the original fifty-one (51) were obtained. They were associated with total variance percentages varying from 67.6% to 84.3%. From the same perspective, the numbers of singlets, in these solutions, ranged from zero to six and the number of doublets, from four to nine.

Solutions with a smaller number of scales were appealing for reasons of parsimony but resulted in numerous undesirable split loadings and disappointing percentages of total variance explained.

The most desirable solution had to maximize the number of items to be retained in the solution while restricting the number of scales to a minimum (i.e., so each scale is composed of many items). At the same time, the ideal solution had to explain as much of the total variance as possible while including as few doublets and singlets as possible, yet keeping items with high communalities. For principal components analysis, Kim and Mueller (1978a, 1978b) recommended to interpret only scales with at least three variables per component. Taking all these constraints into account led to a solution that constitutes the best possible compromise with the present data set.

The retained solution has fifteen scales, as initially suggested by both the Kaiser criterion and the Scree Plot. It explains 82.342% of the total variance, which is a satisfactory proportion, and includes forty-seven of the initial fifty-one items. It presents only one singlet and five doublets.

Appendix X presents the percentage of variance associated with all components of this “winning” solution along with the cumulative percentages. Table 7 is an excerpt displaying the first fifteen components that constitute the final solution. The corresponding Scree Plot appears in Appendix Y.

Table 7

Fifteen First Eigenvalues and Explained Variance in the Final Principal Components Analysis

Component	Initial Eigenvalues		
	Total	% of Variance	Cumulative %
1	6.557	13.951	13.951
2	5.811	12.363	26.314
3	3.694	7.859	34.173
4	3.440	7.320	41.493
5	2.814	5.987	47.480
6	2.541	5.405	52.885
7	2.086	4.439	57.324
8	1.841	3.918	61.242
9	1.735	3.692	64.934
10	1.638	3.484	68.419
11	1.564	3.328	71.747
12	1.476	3.140	74.886
13	1.322	2.813	77.699
14	1.146	2.437	80.137
15	1.011	2.152	82..289

The study of the loadings of the rotated component matrix (Appendix Z) leads to the identification of the scales and corresponding items. Because the Varimax rotation was chosen, the resulting scales or components are orthogonal (uncorrelated) to one another. It can be called a simple structure from Thurstone's terminology (Thurstone, 1931) because each item or variable has a large loading on only one scale and small loadings on all other components.

Guadagnoli and Velicer (1988) claim that if a scale possesses four or more variables with loadings above .60, the pattern may be interpreted confidently regardless of the sample size. Three of the fifteen resulting components do meet this description. Of the six components that comprise three items (and therefore clearly cannot have four or more items with loadings greater than 0.6), five have all of their loadings greater than 0.50, which appears a more realistic yet acceptable threshold given the limited number of participants in this study. The five doublet components have all of their item loadings higher than 0.5 which also appears as a relatively encouraging result.

As pointed out by Rummel (1970), beyond the statistical results, the interpretability of the components remains a most important condition. The defining variables, i.e., the items with loadings in the .70s and .80s, are typically orienting the choice of a name or label for a scale. Appendix AA presents the components composition, loadings, and initial label. It is to be noted that, although all components were given an initial label as a result of the Principal Components analysis, not all components or scales were subsequently retained after the Reliability procedure.

It was important to appraise the internal consistency of these scales through a Reliability analysis to establish which ones were robust enough to be confidently interpreted. Moreover, within a scale, the status of each item needed to be assessed to determine whether it contributed or not to the cohesion of the scale and consequently, whether it should remain in the scale. The following section presents the results of the reliability analysis that addressed all of these issues.

Reliability Analysis

In this study, there were a priori dimensions (see Appendix BB) around which the survey had been constructed. The scales emerging from the principal components analysis tap these categories in some cases (e.g., comfort in program, commitment and self-discipline, etc.) but also suggest new and unanticipated scales (e.g., eagerness to get the best out of class, having a "Physics is Within my Reach" attitude, etc.).

A good scale is as homogenous as possible (i.e., its items all measure a similar concept) and is not overlapping with what the other scales are measuring. The Cronbach's alpha coefficient (Cronbach, 1951) has been identified as the most popular measure of internal consistency (Hogan, Benjamin, & Brezinski, 2000; Li, Rosenthal, & Rubin, 1996) in the social science literature.

The reliability procedure and the resulting Cronbach's alphas give indications on the robustness of such scales and on whether the items of the scale measure something similar. The alpha "if item is deleted" provides information on whether a specific item contributes to a scale and if it should be kept or deleted from a subsequent run of the reliability analysis.

Frisbie (1988), Nunally (1978) and Spector (1992) recommend that the standardized alpha be greater or at least equal to 0.70 to guarantee a good internal consistency of the scale. Similarly, their recommended threshold for the item-total correlation of each specific item is 0.20, to include an item in a scale. Given the exploratory nature of this study and the limited number of items per component, a threshold of 0.5 for the standardized alpha was used, as presented in Santos (1999) for exploratory studies and as recommended in earlier work by Nunally (1967) with a special care for the interpretability (Rummel, 1970) of the resulting scales.

The results for each component are reported below along with the resulting decision made about each scale and its constituents. When a scale was judged robust enough, its items were interpreted on the basis of the concept they have in common and a final label was assigned to the scale. Table 8 presents the reliability analysis for the first scale.

Table 8
Reliability Analysis for Scale 1

Item[13]	Adj. Mean	Std. Dev.	N	Corrected Item-Total Correlation	Cronbach's Alpha if Item Deleted
1A1_11	5.13	1.72	51	.744	.725
2A1_50	5.20	1.37	50	.720	.724
1A2_73	5.51	1.22	50	.606	.770
2E3_64	4.50	1.53	50	.345	.805
3H3_43	5.26	1.58	49	.592	.756
2B3_52	5.02	1.71	50	.417	.798
3E4_45	5.22	1.73	51	.466	.776

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[13] In the label 1A1_11, for instance, « 1A1 » refer to the code of the item and "11" to it original position in the survey.

Number of items in the scale: 7
Standardized Cronbach's Alpha: 0.820
Lowest Item-Total Correlation: 0.345
Highest Item-Total Correlation: 0.744

This first group of items constitutes a robust scale. Its standardized alpha (0.820) is clearly greater than the commonly recommended 0.70. The lowest item-total correlation (0.345) is above the threshold and no item, if deleted, would increase the overall standardized alpha. Consequently, no item needed to be removed and this scale can confidently be interpreted. It has high loadings (see Appendix AA) from items pertaining to "Comfort in program" or having a sense of belonging and being in the right place or doing the right thing. Table 9 presents the reliability analysis for the second scale.

Table 9
Reliability Analysis for Scale 2

Item	Adj. Mean	Std. Dev.	N	Corrected Item-Total Correlation	Cronbach's Alpha if Item Deleted
2C5_28	5.44	1.67	51	.615	.715
2C2_71	5.76	1.38	50	.700	.700
2C1_58	4.45	1.98	51	.512	.756
3D3_32	3.57	1.59	51	.594	.724
2F3_70	3.78	1.87	50	.410	.787

Number of items in the scale: 5
Standardized Cronbach's Alpha: 0.792
Lowest Item-Total Correlation: 0.410
Highest Item-Total Correlation: 0.700

This second component is also a robust scale with a standardized alpha of 0.792. No item needed to be removed since all of the item-total correlations were sufficiently high. There is no item that if deleted would cause an increase in the overall standardized alpha either. The scale could confidently be interpreted and labelled: it appears to be strongly associated with "Strategic and intentional preparation for exam and problem-solving assignments". Table 10 displays the results of the reliability analysis for the third scale.

Table 10

Reliability Analysis for the Scale 3

Item	Adj. Mean	Std. Dev.	N	Corrected Item-Total Correlation	Cronbach's Alpha if Item Deleted
2C3_53	5.02	1.88	51	.499	.750
2B4_65	2.86	1.53	50	.389	.772
4A1_14	3.29	1.50	51	.625	.717
4A2_15	3.14	1.84	51	.648	.705
2E4_72	4.14	1.85	50	.540	.737
1C2_49	2.29	1.08	51	.476	.758

Number of items in the scale: 6
Standardized Cronbach's Alpha: 0.780
Lowest Item-Total Correlation: 0.389
Highest Item-Total Correlation: 0.648

No items were needed to be deleted from this scale given their individual item-total correlations or alphas 'if items were deleted'. The overall standardized alpha was sufficiently high as well to allow for a confident interpretation of the concept that this set of items measures. "Staying up-to-date strategies" seemed to be related to this third scale given its high loadings. Table 11 presents the analysis of reliability for the fourth scale.

Table 11

Reliability Analysis for Scale 4

Item	Adj. Mean	Std. Dev.	N	Corrected Item-Total Correlation	Cronbach's Alpha if Item Deleted
2G1_60	5.43	1.33	51	.472	N/A
2F2_59	4.94	1.48	51	.472	N/A

Number of items in the scale: 2
Standardized Cronbach's Alpha: 0.641
Lowest Item-Total Correlation: 0.472
Highest Item-Total Correlation: 0.472

Because this component contained only two items (a doublet) no alphas if an item were to be deleted could be produced, since deleting any of the two items would cause the complete loss of the scale. A single item cannot form a scale. The standardized alpha for this component was acceptable and given the high loadings associated to its two items in the principal component analysis (see Appendix AA), this fourth group of items can also be interpreted: it relates to the "Construction of personal meaning".

Given the exploratory nature of this study, it is conceptually interesting to examine all of the themes emerging from the principal components analysis. Each component consists of a group of items that correlate together and express a particular dimension of the survey. However, and despite high loadings and an acceptable Cronbach's Alpha, it would not be appropriate to express confidence in a scale that contains only two items. What this situation suggests is that such an emerging dimension should be addressed specifically in the form of additional items in a new version of the survey. In other words, components such as Scale 4 bring insight on the themes that should be considered if the validation process of the survey developed for this study were to be brought to a next step.

In the context of this research, only the initial phases of scale development were performed. Consequently, the results associated with Scale 4 should be considered in this light, i.e., as expressing a possible theme as opposed to describing a robust dimension of the survey data. Table 12 displays the results of the reliability analysis for the fifth scale.

Table 12
Reliability Analysis for Scale 5

Item	Adj. Mean	Std. Dev.	N	Corrected Item-Total Correlation	Cronbach's Alpha if Item Deleted
2H2_19	5.54	1.33	50	.489	.389
4C2_66	3.90	1.80	50	.360	.545
3B2_39	3.30	1.76	50	.364	.534

Number of items in the scale: 3
Standardized Cronbach's Alpha: 0.604
Lowest Item-Total Correlation: 0.360
Highest Item-Total Correlation: 0.604

This scale as well had an acceptable standardized alpha and no item could efficiently be deleted to increase it (see the 'alpha if item is deleted' column). The theme emerging from this scale seemed to pertain to an: "Eagerness to get the best out the class". Table 13 presents the results for the reliability analysis of the sixth scale.

Table 13
Reliability Analysis for Scale 6

Item	Adj. Mean	Std. Dev.	N	Corrected Item-Total Correlation	Cronbach's Alpha if Item Deleted
2H1_24	5.18	1.48	50	.488	.617
1E1_25	5.46	1.73	50	.500	.605
1E2_26	5.74	1.59	51	.528	.562

Number of items in the scale: 3
Standardized Cronbach's Alpha: 0.691
Lowest Item-Total Correlation: 0.488
Highest Item-Total Correlation: 0.528

This scale seemed related to "Commitment and self-discipline". No items needed to be removed, on the basis of the 'alpha if item is removed' and the overall standardized alpha was quite reasonable. Table 14 displays the results for the reliability analysis of the seventh scale.

Table 14
Reliability Analysis for Scale 7

Item	Adj. Mean	Std. Dev.	N	Corrected Item-Total Correlation	Cronbach's Alpha if Item Deleted
1E3_57	5.63	1.22	51	0.404	0.202
3G1_67	3.96	1.70	50	0.181	0.382
2G2_29	3.22	1.43	47	0.113	0.467

Number of items in the scale: 3
Standardized Cronbach's Alpha: 0.434
Lowest Item-Total Correlation: 0.113
Highest Item-Total Correlation: 0.404

This scale, despite reasonable loadings of its items (see Appendix AA), did not display a satisfactory standardized alpha to qualify as a robust scale. This implied that it did not have a good and sufficient internal consistency and was consequently not retained for further analyses of the results. Table 15 presents the initial results for the reliability analysis for the eighth scale.

Table 15
Initial Reliability Analysis for Scale 8

Item	Adj. Mean	Std. Dev.	N	Corrected Item-Total Correlation	Cronbach's Alpha if Item Deleted
3C2_34	4.99	1.63	48	0.327	0.211
2F5_38	5.63	1.27	51	0.157	0.512
1D1_22	4.23	1.57	51	0.316	0.234

Number of items in the scale: 3
Standardized Cronbach's Alpha: 0.424
Lowest Item-Total Correlation: 0.157
Highest Item-Total Correlation: 0.327

Given the low overall standardized alpha and the alpha if item is deleted of 0.512 for the second item of the scale, a new run was conducted keeping only the first and the third items (see Table 16 below).

Table 16
Second Reliability Analysis for Scale 8

Item	Adj. Mean	Std. Dev.	N	Corrected Item-Total Correlation	Cronbach's Alpha if Item Deleted
3C2_34	4.99	1.63	48	0.334	N/A
1D1_22	4.23	1.57	51	0.334	N/A

Number of items in the scale: 2
Standardized Cronbach's Alpha: 0.511
Lowest Item-Total Correlation: 0.334
Highest Item-Total Correlation: 0.334

Following the second iteration, the standardized alpha was acceptable and the scale could be interpreted as pertaining to "Efficiency in Dealing with Challenging Things in Physics". However, for similar reasons to those already presented with the description of the results for Scale 4 (i.e., the presence of only two items in the scale), the results of Scale 8 should be considered as expressing a possible theme emerging of the survey data as opposed to depicting a robust scale. Table 17 presents the reliability analysis for the ninth scale.

Table 17
Reliability Analysis for Scale 9

Item	Adj. Mean	Std. Dev.	N	Corrected Item-Total Correlation	Cronbach's Alpha if Item Deleted
2E2_56	5.78	1.12	51	0.571	N/A
3C4_37	5.90	1.46	51	0.571	N/A

Number of items in the scale: 2
Standardized Cronbach's Alpha: 0.727
Lowest Item-Total Correlation: 0.326
Highest Item-Total Correlation: 0.326

This scale had a good internal consistency (i.e., 0.727) and its items had been associated with high loadings in the principal components analysis. It was labelled: "Meaning of Understanding Physics". Because of the contribution of only two items, however, the interpretation of the results for this scale should be limited to indicating a potential theme emerging from the data. Table 18 presents the results to the reliability analysis for the tenth scale.

Table 18
Reliability Analysis for Scale 10

Item	Adj. Mean	Std. Dev.	N	Corrected Item-Total Correlation	Cronbach's Alpha if Item Deleted
2E1_55	4.47	1.78	51	0.356	0.101
4C1_51	5.69	1.57	51	0.262	0.303
2A2_61	3.62	1.60	50	0.145	0.505

Number of items in the scale: 3
Standardized Cronbach's Alpha: 0.413
Lowest Item-Total Correlation: 0.145
Highest Item-Total Correlation: 0.356

Given the low standardized alpha for this scale and the alpha if the item is deleted for the third item, a second run of the analysis was attempted. However, performing a rerun of the reliability analysis with the first and second items only resulted in a standardized alpha of only 0.450. Consequently, this scale was not retained for further analysis. Table 19 presents the reliability analysis for the eleventh scale.

Table 19
Reliability Analysis for Scale 11

Item	Adj. Mean	Std. Dev.	N	Corrected Item-Total Correlation	Cronbach's Alpha if Item Deleted
3D2_35	3.98	1.91	51	0.300	N/A
3C3_44	5.16	1.27	51	0.300	N/A

Number of items in the scale: 2
Standardized Cronbach's Alpha: 0.461
Lowest Item-Total Correlation: 0.300
Highest Item-Total Correlation: 0.300

This scale did not prove to have a good internal consistency: the standardized alpha was judged too low and this pair of items was not retained for further analysis. The twelfth component being a singlet (i.e., a component containing only one item), it could not be eligible as a scale and was consequently not retained in the forthcoming analyses, despite its high loading (see Appendix AA). Table 20 displays the results of the reliability analysis for the thirteenth scale.

Table 20
Reliability Analysis for Scale 13

Item	Adj. Mean	Std. Dev.	N	Corrected Item-Total Correlation	Cronbach's Alpha if Item Deleted
1D2_23	5.57	1.62	51	0.333	N/A
2F1_63	4.02	1.39	50	0.333	N/A

Number of items in the scale: 2
Standardized Cronbach's Alpha: 0.526
Lowest Item-Total Correlation: 0.333
Highest Item-Total Correlation: 0.333

This standardized alpha was close to the threshold but met the conditions for this study, at least to be interpreted. The interpretation of this scale led to the following label: "Structured and Systematized Approach". However, as explained previously, the results associated with a two-item scale should be considered as tentative. Table 21 displays the reliability analysis results for the fourteenth scale.

Table 21
Reliability Analysis for Scale 14

Item	Adj. Mean	Std. Dev.	N	Corrected Item-Total Correlation	Cronbach's Alpha if Item Deleted
3E2_42	3.76	1.52	51	0.190	N/A
2F4_41	3.54	1.69	51	0.190	N/A

Number of items in the scale: 2
Standardized Cronbach's Alpha: 0.320
Lowest Item-Total Correlation: 0.190
Highest Item-Total Correlation: 0.190

This scale, despite relatively high loadings (see Appendix AA), clearly did not meet the conditions to be retained for subsequent analyses. The Table 22 presents the results related to the reliability analysis of the last scale.

Table 22
Initial Reliability Analysis of Scale 15

Item	Adj. Mean	Std. Dev.	N	Corrected Item-Total Correlation	Cronbach's Alpha if Item Deleted
3D1_33	4.28	1.54	51	0.230	0.572
3C5_36	4.64	1.78	51	0.398	0.314
4C3_68	5.04	1.81	50	0.392	0.324

Number of items in the scale: 3
Standardized Cronbach's Alpha: 0.516
Lowest Item-Total Correlation: 0.230
Highest Item-Total Correlation: 0.398

This standardized alpha was judged sufficient. Although the "alpha if item is deleted" of the first item seemed to suggest that a higher standardized alpha could be obtained via a rerun of the Reliability procedure, this option was not considered to be an improvement of the robustness of the scale since it reduced its number of items to only two. The Scale 15 was consequently maintained in its original structure (i.e., three items) for further analyses and associated with the theme "Having a 'Physics is Within my Reach' Attitude".

As a result of these analyses, six scales out of the fifteen (i.e., Scales 1, 2, 3, 5, 6, and 15) could be considered as robust and reliable. These shared four conditions: a) their items presented high loadings as a result of the Principal Components analysis, b) they displayed good internal consistency as a result of the Reliability analysis, c) they were still constituted of at least three items (Kim & Mueller, 1978a, 1978b) after the Reliability procedure, and d) they presented good interpretability (i.e., a common concept could be identified). The themes associated with these six scales could be confidently interpreted and considered for further analyses.

Four scales with only two constituting items (i.e., Scales 4, 8, 9, and 13), despite their sufficient Cronbach's Alphas and high loadings, had to be considered as interesting pairs of items instead of robust scales. The value of these doublets resided mostly in their potential for suggesting themes that could be explored in a future revision of the survey. In the context of this study, however, their contribution remains limited.

With reliable scales established, the results of the survey could be analyzed. The emerging elements related to approaches to learning and perceptions of the participants about their role as physics students (Research Question 1) could be identified. These results are presented in Chapter 4.

Multivariate Analysis of Variance and Segmentation

To bring additional insight on the various characteristics and perspectives among physics students, the dominant traits emerging from the survey data were identified through a segmentation of values of the variables. The segmentation was performed in the following way: to be considered as a dominant trait for a particular individual, the score of that student on that specific variable needed to be equal to or greater than 5 (out of a maximum of seven on the standardized scales). For each variable, the number of students displaying a dominant trait was tallied and students' profiles were derived. A multivariate analysis of variance was performed on the remaining scales as well as on their variable constituents to verify possible distinctions between the major and honours students' patterns of answers.

Classroom Observations

During the classroom observations, extensive field notes were taken to document the following: the contents and topics being addressed, the classroom context, the teaching approach(es) used by the professor, the conceptions of physics learning supported or challenged in the course, the students' involvement and participation, the cognitive processes and problem-solving abilities that were modelled, scaffolded and/or encouraged in the course, as well as whether the students actually had an opportunity to engage in such cognitive processes and problem-solving during the course.

In addition to these field notes, because classroom observation entries were systematized via observation grids (Appendix N), it was possible to generate a frequency count of the efficacy and relevance of various instructional techniques and features. The number and scores of each feature and technique were compiled. Then, combination charts were generated using Excel.

For the "Instructional Techniques" part of the grid, inspired by the *Grille d'observation sur les techniques d'enseignement* (Cabral et al., 1997), a total of nine (9) graphs were generated to illustrate the various instructional techniques observed. This combination of chart types made easier and more visual the evaluation of the utilisation of a specific technique over the course of the semester, at least for the dates that the classrooms were observed. It also allowed for the amalgamated presentation of the results pertaining to two techniques or observed elements that belonged together and would be best illustrated within the same graph, e.g., "asking questions to students" and "allowing enough time for them to answer," or "students asking questions to professor" and "professor answering students' questions."

For the "Instructional Features" part of the grid, adapted from Dona M. Kagan's (1990) *Configuration Checklist for Evaluating a Teaching Performance*, a global combination graph (multiple series column chart and line chart) was obtained to summarize the twenty-four features observed (pertaining to six different categories). The features were placed on the X axis and color coded by category. During each class observation, the various instructional features were either observed or not. Since there were thirteen observations, this number of occurrences was presented in the Y axis. At the end of each classroom observation, the level of implementation of each observed feature, when applicable, had been rated and this score is presented on a secondary Y axis with its own scale to facilitate the global appraisal of the entire set of instructional features.

The results pertaining to the classroom observations data, including the field notes and the observation grids, facilitated the systematic identification of the determining characteristics of this instructional context.

A simplified version of the four commonplaces of teaching (Schwab, 1973) served as a framework to organize the description of both instructional contexts in Chapter 4. A brief review of each commonplace is offered here.

Schwab's Four Commonplaces (Schwab, 1973)

The first commonplace is the *subject matter* (i.e., "the scholarly materials under treatment and the discipline from which they come from," p.502). Schwab argued against a narrow notion of subject matter and insisted that students be offered a variety of conceptions of a discipline (S. Fox, 1985). In the context of this study, however, the description of the subject matter is purposefully limited to what can be described in the light of the data collected and, therefore, pertains to the specific course or activities observed along with the topics and sub-domains of physics that they addressed.

The second commonplace is the *learner*. Again, Schwab's definition is broad and implies an in-depth knowledge of virtually all of the students' attributes including their thinking, feelings, and behaviours. It is not possible to go that far based on the classroom observations or the PBL sessions. However, a number of student characteristics extracted from the demographical items of the survey (already presented in a previous section) complete the observations made in class about the students, their behavior and interactions.

The third commonplace, the milieu, will purposely be restricted to the classroom and to the interactions happening within its boundaries. Schwab would also include the department, the faculty and the whole school, the local culture, the city, the community as well as the family of the participants, their life style and neighborhood, etc. However, in the context of this study, no inferences about such detailed variables were attempted and the descriptions presented in this section remain grounded in the evidence collected.

The fourth commonplace is the teacher. Rather than being as comprehensive as Schwab with details about knowledge, pedagogical decisions, personality traits, political affiliation or rapport with colleagues, the observed instructional techniques and features documented in the observation grids are described in an attempt to capture what a typical lecture in the traditional teaching context does. In the PBL context, a description of the functioning of the sessions is presented. Some aspects of the instructors' pedagogical background and approaches to teaching are also included.

Interviews

Results related to both contexts were complemented by the thematic analysis of the semi-directed interview with the respective instructor. The audio-taped interviews with both instructors were transcribed verbatim. Each instructor had been asked to focus on a specific instructional situation that was typical of his usual teaching context. Consequently, the analysis of answers made it possible to distinguish between the perspectives of a professor who normally uses a traditional approach to teaching and one who uses a PBL approach on a regular basis. The NVivo qualitative software package was used in doing the analysis of the interviews. The emerging themes and professor's and tutor's perspectives on teaching and learning in physics are discussed in a separate section of Chapter 4.

Problem Sets

The other aspects of the data collection, namely the pen-and-paper solutions to electromagnetism problems, were scored for the presence and quality of the indicators of the various cognitive processes and problem-solving abilities under investigation in this study.

Indicators Assessment and Coding

There were three specific cognitive processes under investigation (metacognition, critical thinking, and physical intuition) and each of them was broken down into three indicators. Each indicator was linked to specific variables. The presence (zero or one coding) and quality (on a scale of 1 to 4; 1 being poor and 4 excellent) of the variables were assessed and subsequently combined into an indicator score. The different indicator scores for a specific cognitive process were aggregated to obtain an overall index on a scale of 100 points.

Another type of cognitive ability was also of interest in this study: problem-solving. Problem-solving abilities were evaluated through four principal indicators, each of which was also linked to a number of variables. Again, the presence and quality of the features were assessed and the scores translated into an overall problem-solving index. The only difference in nature with the problem-solving indicators (unlike the other cognitive processes indicators already mentioned) is that they were not *explicitly* asked of the students as a part of the instructions they were provided when completing the pre- or post-test. Nonetheless, all are desirable features occurring among good and expert problem-solvers, as shown in the literature. They were consequently closely investigated.

Metacognition indicators assessment and coding.

The three indicators considered for metacognition were: a) planning skills and justification, b) application of the plan and readjustments if necessary, and c) accuracy of the level of confidence in the robustness of plan and exactness of solution.

The "planning skills and justification" indicator broke down into two variables: plan and justification. When present, each feature could be assessed, in terms of its quality, on a scale of one (poor) to four (excellent). More specifically, criteria such as sufficiency and exactness of proposed steps, logical progression and correct reasoning, and appropriateness of the use of concepts and relationships were used in coding the plans' quality. An example of the more detailed criteria associated with the appraisal of the quality of a plan is presented in Appendix CC. The quality, relevance and level of articulation in justifying the various steps of the students' plans were also assessed on a scale of one (poor) to four (excellent). This "planning skills and justification" indicator and its constituting features were specifically addressed by section 1A in both the pre- and post-tests.

For the "application of the plan and readjustments" indicator, the presence of the enactment of the plan as laid out, as well as any evidence of modification to the initial plan if necessary, were tallied. When present, these features were also assessed for their quality on a scale of one (poor) to four (excellent). More specifically, the application of the plan aspect pertained to how closely the actual solution matched the initial action plan and how successful its application was. Readjustments and modifications to the initial plan were evaluated in terms of their relevance to the context, level of articulation, and potential in improving the initial plan towards a more appropriate and robust one.

Alternately, students could show evidence of monitoring by explaining how they had tested and made sure that their plan was good and, therefore, did not need to be altered. This second indicator of metacognition was specifically addressed in section 1C of both the pre- and post-tests.

The "accuracy of the level of confidence in the robustness of plan and exactness of solution" indicator included two variables: accuracy of the confidence about the plan and accuracy of the confidence about the solution. In this case it was the students' personal rating of both levels of confidence (portion 1D of the pre- and post-test) that was assessed rather than their plan or solution. The students used a scale of minus three (-3) to plus three (3), where minus three (-3) meant that they were "not confident at all" about the feature, three (3) meant that they were "totally confident" and zero (0) indicated that they were neutral.

The students' self-assessments of their confidence levels were contrasted with the *actual* robustness of their plan and exactness of their solution in terms of their *accuracy*. A scale of minus three (-3) to plus three (3) was used in this case too, but the meaning of the numbers, as assigned by the researcher, was different. Here, minus three (-3) was used by the researcher to qualify a situation where the students completely *underestimated* the quality of their plan or solution (e.g., an excellent plan that the student nonetheless felt completely non-confident about). In a similar fashion, plus three (3) indicated a situation where the students completely *overestimated* the quality of their plan or solution (e.g., a pour solution about which a student was unrealistically confident).

In other words, it was the *accuracy* of the self-evaluation that was assessed and coded, not the actual quality of the plan or solution. Minus one (-1) and minus two (-2), as well as plus one (1) and plus two (2) provided intermediate indices to appraise the degree of underestimation or overestimation of the students' self-confidence in their plans or solutions, when applicable. A student who demonstrated an accurate and realistic self-evaluation, regardless of whether the plan or solution was in fact robust or weak, was given a code zero (0). As a matter of fact, zero corresponded to an appropriate and objective evaluation of the level of confidence that the students could realistically have in that specific feature (i.e., neither underestimated nor overestimated).

As in other indicators, these variables were combined into an indicator score as well. However, while the previous indicators had constitutive features that could easily be combined together since they were already all on a scale of one to four, the levels of accuracy codes needed a supplemental step to be transposed on a scale of one to four. In this 'accuracy of the self-evaluation' new scale, one indicated a definitely unrealistic evaluation of the students' level of confidence, regardless of whether it was a clear underestimation (-3) or a clear overestimation (3). Two indicated a somewhat unrealistic evaluation (either coming from a -2 or +2 coding by the researcher) and 3 corresponded to a relatively good evaluation (coming from the -1 and +1 codes of the researcher). Four indicated an accurate and realistic evaluation of the level of confidence (coming from the zero codes of the researcher). The combination of all indicator scores led to an overall index of metacognition.

Appendix DD presents a summary table of the indicators of metacognition, their constitutive variables and descriptions, the nature of the coding scheme utilized along with the section of the problem sets they corresponded to.

Appendix EE presents an illustration of a very general plan that does not address specifically the problem at hand (problem 1.1 of the pre-test). Steps with a label such as "Draw a diagram" or "Write down relevant formulas" are not specific enough to provide evidence of the students' understanding of the specific problem and hence could be used for any problem. As indicated in the Appendix CC, when assessed for its quality, such a plan resulted in a code "1" or "poor" on a scale of one to four. It can be noted that the step four written down by the student says: "Solve the problem", which is what this plan should have detailed in the first place.

This is a typical example that suggests that students are not familiar with planning when they solve problems. They are not always clear on what should be included in a robust plan and how it could help them achieve a more complete solution. Consequently they tend to be deprived from the potential benefits of such a planning activity on the improvement of their metacognitive and problem-solving abilities.

Appendix FF presents a sample of a detailed plan of action and solution as laid out by a different student answering Problem 1 of the post-test. It is a good example of a quite complete and sound initial plan of action (the quality of the plan was coded "4"). Though the justification for different steps of the plan was limited, particularly in the initial solution plan, it was well articulated and appropriate, especially in the revised versions of the plan, and hence received a code "3". As difficulties arose while solving the problem, the student showed clear evidence of monitoring by successively revising and adjusting her/his plan (the students used subheadings such as "Initial Solution Plan", "Revised Plan Solution", and "2nd Revised Plan Solution" to identify his/her corrections to the initial plan) until reaching a satisfactory solution. The quality of the readjustments and modifications was coded "4". The application of the plan was coded "4" as well. Though the initial plan was not entirely applied as laid out, its subsequent revisions did get translated into action progressively leading to a complete application of the planned actions.

Critical thinking indicators assessment and coding.

Three indicators were considered to document evidence of critical thinking in the problem-solving plans and solutions among the participating students: a) the students' discriminating ability, b) the students' ability to categorize the problem on the basis of their deep and surface features, and c) the students' ability to estimate a realistic range of answers.

The "discriminating ability" indicator was linked to evidence of the students' ability to differentiate between relevant and irrelevant elements of the problem. Supplemental data had been purposefully included in problem 1 of both the pre- and post-tests. These were complementary and accurate data and not meant in any way to mislead. They were simply not essential to the complete and satisfactory solving of the problem. Consequently, whether and how the students used these data provided indications on their ability to discriminate between essential and irrelevant elements when attempting to solve a problem (section 1C of the pre- and post-test). A scale of one (poor) to four (excellent) was used in that case as well to assess this ability.

For the "ability to categorize the problem on the basis of surface and deep structures", the number and correctness of the various elements selected by the students (in the problem portion 1E) were evaluated on a scale of one to four. The "ability to estimate a realistic range of answers" indicator (which was dealt with in the section 1B of the pre- and post-tests) broke down into two variables: the estimate of a range of answers and its justification. Their presence was coded and, when present, their quality was assessed on a scale of one to four.

Appendix GG presents the indicators of critical thinking considered in this study as well as their associated variables, descriptions and coding schemes. Appendix HH displays an example of a realistic range of answers which was coded "4". Not only is the estimate realistic in the given context (problem 1 of the post-test) but its rationale is clear and to the point.

Physical intuition indicators assessment and coding.

Physical intuition was also appraised through three main indicators: a) the ability to anticipate trends or alternatives, b) the ability to clearly identify gaps in one's knowledge or missing information in the problem statement, and c) the ability to generate analogies. The presence of each was noted and, when present, their quality was assessed on a scale of one (poor) to four (excellent). It is in the context of problem 2 (for the pre- and post-tests) that the students' physical intuition was triggered. This problem was designed to be advanced and complex on purpose, while including a number of already familiar elements. The students were not expected to solve this problem but rather to consider how they could tackle it, identify the gaps in their knowledge (or in the problem statement) and, if possible, to describe analogous problems or situations they had already encountered. Appendix II presents the details about the indicators of physical intuition considered in this study along with their associated variables, descriptions, and coding scheme.

Appendix JJ presents an example of an excellent articulation (coded 4) and reasoning on the possible trends to achieve a solution to an unfamiliar problem. The problem (number 2 in the post-test) pertains to concepts not yet seen in class and too advanced to be solved directly by the students. However, this student planned on using the resources at hand (e.g., "First I will read the section in the book on lossy lines") and had a systematic approach to solving this problem based on more familiar and analog situations (e.g., "Set up a circuit diagram similar to Fig 9.10 to try to include losses", "[Write] out equations for V trying to incorporate alpha and beta"). The student discussed good strategies that she/he could use to go as far as possible, despite the difficulty of the problem at hand. He/she included making some deductions about the meaning and nature of some unfamiliar concepts and variables that were not defined in the problem statement or textbook, via a careful analysis of their units or drawing a circuit diagram (e.g., "I could also use manipulation of the units in alpha and beta to understand these quantities and how they will affect the equation for V…").

About a third of the students indicated instead that they did not know what some of the variables were or meant and, therefore, did not know how they would deal with this unfamiliar problem. In contrast, the student, whose possible options are presented in Appendix JJ, displays originality and inventiveness in anticipating possible ways to deal with this advanced problem while building on already mastered and related concepts.

Problem-solving indicators assessment and coding.

The four indicators to problem-solving abilities were: a) the ability to recognize and acknowledge assumptions, b) the ability to translate or represent the problem into a graphical form, a sketch, or a pictorial representation, c) the ability to translate written statements into mathematical and physical representations, and d) the completeness and accuracy of solution, regardless of the match with or quality of the plan.

The "ability to recognize and acknowledge assumptions" indicator, when present, was assessed on a scale of one to four. Here it was the accuracy and the level of elaboration of the expressed assumption(s) that was evaluated. The indicator “ability to translate the problem in a graphical representation” pertained to the use of graphics, sketches, or pictorial representations. Again it was their conceptual exactness and the extent to which it was representative and relevant to the context of the problem that was evaluated and not the artistic elegance or design.

The “ability to translate written statements into mathematical and/or physical representation” was related to the laws, physical concepts and principles, as well as to the equations and relationships referred to and utilized by the students in solving the problem. Their completeness, exactness and representativeness of the problem at hand were evaluated on a scale of one (poor) to four (excellent).

The indicator “completeness and accuracy of the solution” served to assess the overall quality of the solution, regardless of the plan. In other words, in this case whether the solution actually matched the initial plan of action or not, or whether the plan was robust to begin with, were not considered. It was the solution, as a stand-alone feature, that was assessed on a scale of one to four. For instance, some students might have experienced some difficulties in developing and applying a strategic plan (maybe partly due to the novelty of the task and lack of practice with such a request) but nonetheless achieved a good solution to the problem and reached an acceptable answer. This indicator acknowledged the quality and accuracy of the obtained solution, regardless of how or how well it had been planned (or not). The results derived from the assessment and coding of the problem sets are presented in the coming sections.

Appendix KK presents the indicators of problem-solving abilities along with their associated variables, descriptions and coding schemes. Appendix LL shows an example of detailed and complete graphic that describes accurately the problem context (problem 1 of the post-test).

Presentation of the Results Pertaining to the Problem Sets

Descriptive general statistics on the metacognition, critical thinking, physical intuition, and problem-solving general indices and specific indicators were obtained to document the prevalence and robustness of these cognitive processes among the participating students. A multivariate analysis of variance (MANOVA) was also conducted to compare the results on the pre- and post tests on the same indices. These results are presented in Chapter 4.

A comparative 3-D bar chart summary of the separate variables was obtained to allow for an initial and visual appraisal of the results. Mostly, the 3-D bar chart made visual potential significant differences between the pre- and post-tests that needed to be formally addressed with an analysis of variance.

Tests of Group Differences

An *a priori* hypothesis was that no significant distinction between the pre- and post-test would be obtained for the students who were not involved in the PBL intervention (traditional teaching). The eighteen (18) days that separated the pre- and the post-test were not likely to allow for a significant maturation and integration of the content that could be measured in the problem-solving exercises because of the stability of the instructional context. It was expected, however, that the students who had participated in the PBL activities might have developed a more confident and effective approach to problem-solving, possibly visible in their approach to the second problem of each set that intentionally addressed topics and concepts that were unfamiliar and beyond their current level.

A repeated measures procedure was used to verify these possible differences for significance. To determine whether the PBL students displayed different patterns of metacognition, critical thinking, physical intuition and problem-solving, their pre- and post-tests were analyzed using a two by two mixed factorial design with repeated measures on the second factor. Treatment was a two-level between-subjects factor (traditional teaching or PBL) while time was a two-level within-subjects factor (pre- or post-test). The interaction of time and treatment was tested. Tests of simple main effects were also conducted.

The absence of significant differences between the pre- and post-tests in terms of the prevalence and quality of the measured indicators for the cognitive and problem-solving processes under investigation would have allowed the researcher to pool both the pre- and post-tests results together to describe the students' situation in the light of a bigger data set. However, some significant differences were identified between the pre- and post-tests for both the traditional teaching and PBL students as well as for the entire sample. These results and their interpretations are presented in Chapter 4.

PBL Video-recording

The PBL video recording necessitated a complex set of procedures in order to be analysed. The two PBL sessions led by the physics PBL expert were transcribed verbatim in two separate files. A careful and repeated listening of the tapes was necessary to verify transcriptions. The simplified transcription convention, inspired by Koschman, Glenn, and Conlee (2000) and Siverman (2001) was used in this study and is presented in Appendix MM. Naturally occurring pauses served as segmentation marks and a carriage return was inserted after each. The resulting texts were imported into the qualitative data analysis package NVivo for subsequent coding and analysis.

The coding of the transcripts consisted of a process of selection of the relevant passages in the text and in their association with a describing label. It is an iterative process that requires attentive runs and reruns of the text. Coding categories related to a common theme are called coding trees. Five *a priori* coding trees were systematically used in dealing with the data.

Coding Trees

The first and most straightforward coding tree was the “Speaker” tree, which clearly identified who said what, in the transcription. The combination of both the sound and the image in the video-recording facilitated the positive identification of the speaker for every utterance.

The second (“Tutoring”) and third (“Cognitive Actions”) coding trees were adapted from Frederiksen and Donin (2005, in press) and Frederiksen, Roy, and Bédard (2005, in prep.). Both trees, developed in the context of these authors’ research on tutoring in engineering, offered a comprehensive coverage of the concepts under investigation. The detailed definitions elaborated for each category facilitated the systematic coding of the data. The “Tutoring” tree captured the strategies used by a tutor to convey information and interact with students during the PBL sessions. The “Cognitive Abilities” tree allowed for a specification of the students’ cognitive activities in applying procedures or solving the PBL problem.

The students’ problem solving steps and attempts were also characterized in terms of the aspects of the model solution to the PBL problem they specifically referred to. This fourth coding tree, called “Problem Frame,” depicted the sequence and conditions on the sub-steps necessary to successfully solve the PBL problem. It constituted a direct transposition into nodes and children of the hierarchical model solution to the PBL problem (see Appendix NN). It can be noted that the model solution to the PBL problem had been approved by both the Electromagnetic Waves professor and PBL tutor.

The nature of the activities the students engaged in was also organized with the “Types of Activity” coding tree. The categories of this fifth coding tree addressed the three genres of activities that the students engaged in during the PBL tutored sessions: a) solving the problem, b) working on learning issues, and c) performing PBL-specific tasks or assignments. These categories were designed to be mutually exclusive.

The coding tree design and coding process was sufficiently formalized[14] to claim that the coding of the PBL transcripts was rendered consistent and reliable. The codebook associated with each of these five coding trees is presented in Appendix OO.

Log-linear Analyses

When the coding of the two PBL sessions was completed, the search functions available in NVivo facilitated the retrieval of the information that would allow for the description of each session along with the nature and involvement of the various participants. Interaction matrices, presenting the frequency counts of specific units of coding, made it possible to obtain cross-tabulated categorical variables by using the boolean search functions in NVivo. The analysis of such cross-tabulation tables were done with log-linear analyses (CATMOD procedure of the SAS statistical software package). Contrasts and effects, such as speaker by session, speaker by problem frame, speaker by type of activity, etc., were appraised in this light. Since potential interactions between these variables (e.g., speaker by session by problem frame) were also interesting, a saturated model was requested when running the log-linear procedures.

Log-linear analyses performed on contingency tables are analogous to analyses of variance (ANOVA) performed on continuously distributed factor-responses variables (Lawal, 2003). Log-linear analyses assume that the counts from the table cells have Poisson distributions rather than normal distributions as is the case in ANOVA. The maximum likelihood analysis given by the CATMOD procedure allows to test the independence or by extension, the level of association of a number of variables.

One of the powerful aspects of the log-linear analyses is the possibility to deal with three-way contingency tables (i x j x k), which allows for the analysis of complex models of data otherwise very difficult to investigate.

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[14] The "Problem Frame" and "Types of Activities" coding trees were both discussed and refined in collaboration with Professor Frederiksen.

Log-linear analyses consequently helped to better describe the nature of the PBL sessions and of the interactions between the students and the tutor. This approach also shed light on the processes and cognitive actions that the students engaged in.

The results pertaining to these five bodies of data and their interpretations are presented jointly in the next chapter. The final chapter of this dissertation presents overall conclusions and offers recommendations that can inform future research and practice in physics teaching and learning.

CHAPTER 4 – RESULTS AND INTERPRETATION

Students' Approaches to Learning and Perceptions about Role

The answers to the first research question – about the approaches to learning and general perceptions about their roles of undergraduate physics students – are derived from the analysis of one main data source: the Approaches to Physics Learning and Conceptions of One's Role as Physics Student Questionnaire.

APL/CORPS Results

In this section demographics about the participants are summarized. This is followed by results directly derived from the scale scores and from a more specific look at some individual items.

Demographics

There were fifty-one participants in the first phase of the study who completed the survey. There were twelve females (23.5%) and thirty-nine males (76.5%), ranging from 17 to 24 years of age. Twenty-seven students were studying in the major program in physics while twenty-four were from the honours program. Table 23 presents the distribution by age for the participants of these two cohorts. Table 24 presents the distribution by gender.

Table 23
Age and Program of the Participants to the Survey

Program	Age				Total
	17-18 years	19-20 years	21-22 years	23-24 years	
Majors	2	13	10	2	27
Honours	0	14	10	0	24
Total	2	27	20	2	51

Table 24

Gender and Program of the Participants to the Survey

Program	Gender		Total
	Female	Male	
Majors	10	17	27
Honours	2	22	24
Total	12	39	51

Although most of the participants had English or French as their mother tongue, a variety of other languages were also considered to be the first language (Table 25).

Table 25

Languages Spoken as a Mother Tongue

Language	Frequency	Cumulative Percent
English	21	41.2
French	22	84.3
Equally English & French	1	86.3
Arabic	1	88.2
Chinese	1	90.2
Finnish	1	92.2
Greek	1	94.1
Japanese	1	96.1
Romanian	1	98.0
Spanish	1	100.0
Total	51	

Before commencing studies in their current program, participants had studied in a variety of Canadian and international locations, as it can be seen in Table 26.

Table 26

Places Where Participants Lived Prior to their Current Enrolment

Place of Residence Prior to Current Enrolment	Frequency	Cumulative Percent
Québec	28	54.9
Ontario	8	70.6
Atlantic Provinces	1	72.5
Western Canada	2	76.5
England (Wales)	1	78.4
France	1	80.4
Oman	1	82.4
Qatar	1	84.3
USA	8	100.0
Total	51	

These participants were distributed in two programs almost equally: honours (47.1%) and majors (52.9%) so the next step was to investigate whether these two subgroups tended to distinguish themselves in one way or another and whether this had anything to do with the program of choice. Besides a more demanding academic program offered to the honours students, no *a priori* hypothesis had been made regarding potential differences in the survey between these two cohorts.

Distinctions Between the Major and Honours Cohorts

Multivariate tests were conducted to contrast the scale scores of the major and honours cohorts. Overall, there was no significant distinction between these students (p=0.254). The corresponding table for the multivariate analysis of variance is presented in Appendix PP.

It can be seen from Table 27 that on five of the six scales, the major cohort obtained a score greater than that of the honours cohort. In one out of six scales, the honours students obtained a superior score.

Table 27

Means and Standard Errors of the Major and Honours Cohorts on the Ten Retained Scales

Scale Score (Dependant Variable)	Program Grouping	Mean	Std. Error
Comfort in Program	Honours	5.402	.221
	Major	4.877	.216
Prep. for Exam & Probl-Solv	Honours	4.651	.138
	Major	4.732	.135
Staying Up-to-date Strategies	Honours	3.565	.259
	Major	3.690	.253
Get the Best Out of Class	Honours	4.730	.182
	Major	5.026	.178
Commit. & Self-discipline	Honours	5.324	.277
	Major	5.580	.271
Physics is Within my Reach	Honours	4.570	.213
	Major	4.884	.208

When formally contrasting the effects of the program grouping (major vs. honours) for each of the six scales, none of these differences proved significant at the 0.05 level. These univariate tests are presented in the Appendix QQ. It can be noted, however, that had a more lenient threshold such as 0.1 been used, one scale would have been associated with scores significantly higher for the honours students: "Scale 1 – the comfort in program."

Other analyses of variance were also conducted at the item level, taking into account every variable (i.e., item) when running the procedure. Once again, no significant distinction (p=0.415) was observed between the major and honours cohorts for the overall multivariate test (see Appendix RR). However, at the specific level of the items, two significant differences were observed between the two cohorts: they favoured the major students (S03_49 and S05_66). These univariate tests are presented in the Appendix SS and will be addressed in the next section.

Differences at the item level led to additional analyses within each scale of the survey in order to better identify the nature of the students' approaches to learning and perceptions of their role. This approach allowed for a specific identification of the dominant traits displayed by the participants in their responses to the survey.

Students' Profiles

In order to establish students' profiles, the dominant traits emerging from the survey were identified. Given the standardized seven-point Likert scales used in the survey, the individuals with a score equal to or greater than five (≥5) were counted as displaying a high score for that item. The number of individuals presenting a high score on a specific item (along with their associated percentages) are organized in tables (Table 28 to Table 33) for the twenty-seven items of the six final scales.

To be considered a dominant trait of the participating cohort, the concept measured in a specific item had to be associated with a high score for at least 50% of the students. The prevalence of a feature thus contributed to defining the profile of the students in a more descriptive way than simply relying on means since means can be particularly sensitive to fluctuations from outliers.

The profiles were interpreted on the basis of the two cohorts (majors and honours) being pooled together since multivariate analyses showed that there was no overall significant distinction between the two sub-groups. As complementary information, however, the percentages for each cohort are also included in parentheses in the presentation of the results. This data led to several hypotheses, including the case of the two items associated with a significant difference in the univariate tests already mentioned in the previous section (see Appendix SS).

Table 28 to Table 33 present the frequencies and percentages of participants that had a high score (i.e., at least five out of a maximum of seven) for each item pertaining to the various scales. Conclusions on dominant traits (indicated by grey cells) within each scale were derived when at lest 50% of the participants displayed a high score on a specific item.

An asterisk (*) indicates an item that had been recoded prior to all of the numerical analyses. As specified earlier, when an item had a negative phrasing or connotation, the recoding procedure ensured that its score was consistent with the meaning of the construct being measured. Although the original phrasing of the items is presented here, the reader can note that all scores reflect the alignment in the same direction of all items of a same scale, as described by each scale label.

Table 28 presents the scores and dominant traits for Scale 1: "Comfort in program – A sense of belonging, being in the right place and doing the right thing." Every component of this scale is dominant among participants except the comfort with the readings (expressed through the item S01_64) that is prevalent only among the honours students.

Table 28

Scores and Dominant Traits for Scale 1: Comfort in Program

Item Code	Item	All Participants (N=51)	Program	
			Honours (N=24)	Major (N=27)
S01_11	How certain are you that your current choice of program of study is the best one for you?	34/51 (66.7)	18/24 (75.0)	16/27 (59.3)
S01_50	In physics this year, I prefer course work that is challenging so I can learn new things.	34/50 (68.0)	19/24 (79.2)	15/26 (57.7)
S01_73	Which of the following best describes how you feel about your current program of study?	43/50 (86.0)	20/23 (87.0)	23/27 (85.2)
S01_64 (*)	I often find that I have been reading for class in physics this year but don't know what it was all about.	24/50 (48.0)	13/23 (56.5)	11/27 (40.7)
S01_43	A good understanding of physics is necessary for me to achieve my career goals. Good grades in my physics courses this year are not enough.	29/49 (59.2)	16/23 (69.6)	13/26 (50.0)
S01_52	I make sure that I keep up with the physics weekly readings and assignments this year.	33/50 (66.0)	14/24 (58.3)	19/26 (73.1)
F01_45 (*)	Physical laws have little relation to what I experience in the real world.	32/51 (62.7)	15/24 (62.5)	17/27 (63.0)

Overall, the results for this scale indicate that the participants are comfortable in their current physics program and have a positive feeling about being enrolled in their program.

Table 29 presents the scores and dominant traits for Scale 2: "Strategic and Intentional Preparation for Exam and Problem-solving Assignments"

Table 29
Scores and Dominant Traits for Scale 2: Preparation for Exam and Assignments

Item Code	Item	All Participants (N=51)	Program	
			Honours (N=24)	Major (N=27)
S02_28	When preparing for a physics exam, I try to anticipate the questions that I think might be included and study them.	35/51 (68.6)	14/24 (58.3)	21/27 (77.8)
S02_71	When studying for an exam in physics, I practice solving problems similar to what I expect to get in the test.	43/50 (86.0)	20/23 (87.0)	23/27 (85.2)
S02_58 (*)	When studying for an exam in physics, I memorize formulas and equations.	14/51 (27.5)	7/24 (29.2)	7/27 (25.9)
S02_32 (*)	The most crucial thing in solving a physics problem is finding the right equation to use.	27/51 (52.9)	14/24 (58.3)	13/27 (48.1)
S02_70	When confronted with difficult material or problems in physics this year, I try to think up possible solutions and then systematically check them out.	21/50 (42.0)	8/23 (34.8)	13/27 (48.1)

Among the strategic approaches used by the students, it can be noted that systematically testing possible solutions in the face of difficult material or problems is not prevalent (item S02_70). In the context of this study, rote memorizing was not conceptualized as consistent with strategic preparation for exams and assignments. The results of item S02_58 reveal that rote memorizing of formulas is still a common approach among the participants.

However, it is most interesting to see the presence of strategies such as "anticipate the questions that might be included in an exam" (items S02_28) and "practice problems similar to what is expected for the test" (item S02_71) among the majority of students. The intentionality and the conscious effort that these strategies require from the students in order to anticipate what they will be tested on and prepare themselves accordingly have a strong metacognitive connotation. The students are strategic when preparing for exams and assignments. The results of this scale suggest that second and third year students in physics probably have been able to derive a good understanding of what an appropriate preparation for exams and assignments entails from their experience as physics students.

Table 30 presents the scores and dominant traits for Scale 3: "Staying Up-to-date Strategies". Besides consistently revising their notes and readings (item S03_53) and promptly clarifying any confusing part in their notes (item S03_72), none of the other strategies to stay up-to-date investigated in this scale appear to be prevalent.

Table 30

Scores and Dominant Traits for Scale 3: Staying Up-to-date Strategies

Item Code	Item	All Participants (N=51)	Program	
			Honours (N=24)	Major (N=27)
S03_53 (*)	I rarely find time to review my notes or readings in physics before an exam this year.	34/51 (66.7)	19/24 (79.2)	15/27 (55.6)
S03_65	I work on practice exercises and end of chapter problems even if they are not required.	11/50 (22.0)	6/23 (26.1)	5/27 (18.5)
S03_14	How would you rate the degree of the students' participation in your physics classes this year?	10/51 (19.6)	6/24 (25.0)	4/27 (14.8)
S03_15	Using a similar scale, how would you rate your own participation in your physics classes this year?	11/51 (21.6)	5/24 (20.8)	6/27 (22.2)
S03_72	If I get confused taking notes in physics lectures this year, I make sure to sort it out after class.	27/50 (54.0)	11/23 (47.8)	16/27 (59.3)
S03_49	How many times did you go to your professor(s) for help with your physics course work this year.	5/51 (9.8)	0/24 (0.0)	5/27 (18.5)

Item S03_65, for example, suggests that students are already busy with the mandatory elements of their classes and find little time for extra work, even though practice can contribute to strengthening their understanding, provide them with a larger variety of problems and contexts to verify their mastery of the topics studied, and help them build confidence in their ability to tackle a wider range of problems.

Items S03_14 and S03_15 show that students maintain a low level of participation in class and do not use this strategy to enhance their classroom experience and overall understanding. This is not a new situation in physics or in science courses in general. The classroom observations conducted by the researcher during this study also led to the conclusion that students are used to a relatively passive role. In other words, most of the time the students limit themselves to silently copying what is written or demonstrated on the board during lectures and rarely ask questions or intervene. Meeting the professor at his office is also a rare initiative for these students (item S03_49).

Table 31 presents the scores and dominant traits for Scale 5: "Eagerness to Get the Best Out of the Class". Overall, this scale suggests that students want to get the most out of their class experience: they want to internalize their understanding, benefit from opportunities to improve their understanding via questions posed to the professor during class time, and get the best grades possible.

Table 31
Scores and Dominant Traits for Scale 5: Get the Best Out of the Class

Item Code	Item	All Participants (N=51)	Program	
			Honours (N=24)	Major (N=27)
S05_19	How important is it for you to get high grades this year?	41/51 (80.4)	18/24 (75.0)	23/27 (85.2)
S05_66	I ask the professor to clarify physics concepts if I don't understand well.	21/50 (42.0)	6/23 (26.1)	15/27 (55.6)
S05_39 (*)	In physics this year, I do not expect to understand equations in an intuitive sense; most must simply be taken as given.	32/51 (62.7)	18/24 (75.0)	14/27 (51.9)

It seems that honours students are more reluctant than major students to ask questions during class (S05_66) and the univariate tests showed that the difference between the scores of the two cohorts of students was significant at the 0.05 level. This is consistent with the results of a previous item (S03_49) which showed that major students go to the professor's office to seek further explanations significantly more often than honours students. It can be hypothesised than honours students might entertain a stronger sense of competitiveness or take more pride in maintaining an image of autonomy and control. The grades are important to most students but they appear even more important to major students. A possible hypothesis to explain why grades seem more important to major students would be that grades might be perceived as a means to establish one's status within a group. In contrast, students in the honours group are already assumed to be strong (because of the requirements of their program) and might consequently depend less on their grades to build their self-image as physics students.

Table 32 presents the scores and dominant traits for Scale 6: "Commitment and self-discipline". Physics programs, either majors or honours, are demanding and this scale appears to reflect the dedication and desire to achieve that students display.

Table 32

Scores and Dominant Traits for Scale 6: Commitment and Self-discipline

Item Code	Item	All Participants (N=51)	Program	
			Honours (N=24)	Major (N=27)
S06_24	I work very hard to get good grades in physics this year.	32/50 (64.0)	15/24 (62.5)	17/26 (65.4)
S06_25	Even when I am tired, I try to complete my assignments in physics this year.	35/50 (70.0)	14/24 (58.3)	21/26 (80.8)
S06_26	I set high standards for myself in my physics classes this year.	38/51 (74.5)	17/24 (70.8)	21/27 (77.8)

Students' commitment and self-discipline is certainly a strong feature and this is also a positive asset considering how demanding their physics programs are.

Table 33 presents the scores and dominant traits for Scale 15: "Having a 'Physics is Within my Reach' Attitude". This scale appears to be linked to a perception about who can do physics and how students can identify themselves as being such a person.

Table 33

Scores and Dominant Traits for Scale 15: Physics is Within my Reach

Item Code	Item	All Participants (N=51)	Program	
			Honours (N=24)	Major (N=27)
S15_33	When learning physics, a student cannot fully understand new material unless she/he relates it to something she/he already knows.	20/51 (39.2)	12/24 (50.0)	8/27 (29.6)
S15_36 (*)	Only very few specially qualified people are capable of really understanding physics.	27/51 (52.9)	13/24 (54.2)	24/27 (51.9)
S15_68	When I can't understand the material in my physics courses this year, I ask another student for help.	37/50 (74.0)	14/23 (60.9)	23/27 (85.2)

It appears that comfort and help-seeking among peers can reinforce such a perception. Promoting the notion that other students can help and be reliable resources in case of difficulty might, therefore, be a positive thing to do.

From this perspective, collaboration and team work can be very positive and empowering for students. The overall scores from Scale 15 tend to suggest that most students feel that understanding physics is actually within their reach. This seems to be aligned with the overall positive feeling expressed about their program (see the analysis of the results for Scale 1).

Summary about the APL/CORPS

The results from the analysis of dominant traits emerging from the survey for each scale show that the advanced students' profile is characterized by a number of self-reported strengths:

- an overall feeling of comfort in their respective physics program;
- a strategic and intentional approach to preparing for examinations and assignments by most students (e.g., trying to anticipate the questions and preparing themselves accordingly, practice solving problems similar to those expected to be in exams, systematic revisions of notes and readings);
- a generally structured and organized way to deal with subject matter content;
- an eagerness to get the most of the course, including high grades, for a majority of students;
- a prevalent commitment, self-discipline and high standards for themselves;
- a 'Physics is within my reach' overall attitude.

These strengths are positive assets that both the adavanced students and instructors can build on in developing effective and empowering approaches to learning. The students' profile also includes a few potentially negative features:

- a generalized low level of class participation;
- a reluctance to go to the professors for help and to some extent to ask questions in class;
- some difficulties in keeping up-to-date.

These less strong features reflect an overall and common perception among the students about their role as physics students as being a relatively passive one. They also reveal a reluctance of the students to interact with the professor, both in and outside of class, even though in all likelihood this could help them keep up with the pace of the course.

Instructional Contexts and Modelling

In answering the second research question, concerning the characteristics of the traditional and PBL approaches to teaching and the extent to which metacognition, critical thinking, physical intuition, and general problem-solving processes are modeled in each context, three different bodies of data were used. For the traditional instructional context, observation grids combined with field notes were the main data source while for the PBL sessions, the video recordings constituted the principal source of information.

Traditional Teaching Context

The traditional teaching context corresponds to the environment surrounding the usual teaching of the professor in his classes of "Electromagnetic Waves". The following sections offer a description of this instructional context organized around Schwab's four commonplaces (Schwab, 1973): subject matter, learner, milieu, and teacher.

The subject matter

The advanced electromagnetism course whose students and professor participated in this study dealt with a number of topics building on subject matter already addressed in introductory classes about electricity and magnetism. The classroom observations began on January 23rd and took place until the end of the semester on April 7th. Thirteen sessions were observed during that period. The semester began with electromagnetic induction, including electromotive force and Faraday's law, self inductance and mutual inductance, reciprocity, energy stored in electric and magnetic fields. Then electromagnetic machinery was addressed (e.g., a.c. and d.c. generators, transformers, a.c. and d.c. motors, etc.). At the heart of the course, in February and March, came the electromagnetic waves which covered concepts as varied as displacement current and Maxwell's equations, wavemotion basics, electromagnetic waves (in free space, in non-conducting media and in conducting media), reflection and transmission at interfaces, Fresnel's equations, Brewster angle and total internal reflection. It is only toward the end of the semester that the transmission lines and waveguides were studied. Direct applications such as co-axial cables, parallel strip line, parallel plates and rectangular waveguides were addressed along the way. Electromagnetic radiation, including accelerated charges and retarded potentials, radiation from oscillating electric dipole and half-wave antenna completed the semester's content matter.

The Learner

A number of demographical characteristics of the students have already been detailed in the previous section. Additional results on the general behavior of the students are described on the basis of the field notes collected during the classroom observations. Figure 4 presents the attendance profile of the students over the course of the semester. As mentioned previously, there were forty-one (41) students registered in the Electromagnetic Waves course. However, during the thirteen classes observed there were never more than thirty-seven students present and no less than twenty-eight. The average attendance in the classroom for the thirteen classroom observations was 32.85 students (with a standard deviation of 2.64). On Monday morning classes (classes began at 8:35 a.m.) particularly, many students seemed sleepy and a number of them (from three to nine) arrived late. One possible explanation is that, as the semester unfolded, the students sometimes became overwhelmed with their work and preparation for exams and became more prone to missing classes. Informal input from students, when they missed a class, suggested that they either made use of the time for studying or for sleeping.

Students tended to occupy the same seats in every class session. Moreover, many pairs or trios of students usually teaming up together in the laboratories of other courses of their program were seated side by side every time the class met. Because there were many unoccupied seats in the classroom, the students tended to be distributed evenly in the entire classroom.

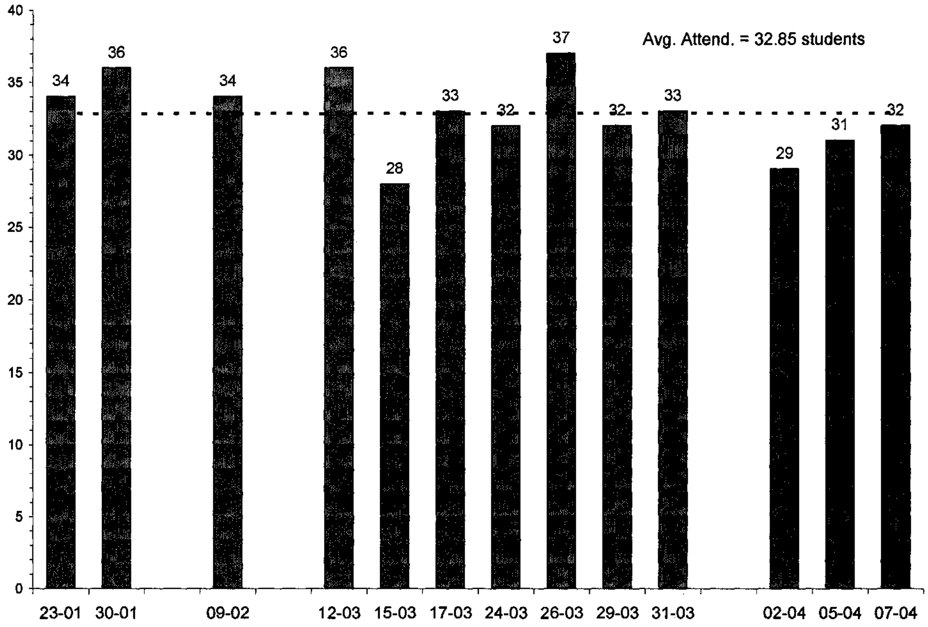

Figure 4. Students' Attendance Profile

On a number of occasions, the professor modeled problem-solving by thinking aloud, as opposed to simply demonstrating algebraic relationships. This gave the students an opportunity to observe expert reflection about a complex topic. On these occasions, the professor slowed down the pace and progressively guided the students' thinking through a series of well chosen questions which led to the heart of the topic. Some questions simply called on remembering facts (e.g., "Does anyone remember polar coordinates?", "What are the units of μ_0?") while other questions forced students to process information toward gaining a deeper understanding (e.g., "Do you really believe this last number here?", "Then you get this wonderful integral which should challenge your integration skills! What do you think is the next thing to do to deal with this integral?"). Step by step, following the students' pace, the professor gave them the opportunity to build on their prior knowledge through guided reasoning and reflection. Such directed thinking sessions were not frequent, however. The typical method of instruction was lecture which served to cover and disseminate as much information as possible in as little time as possible.

It was observed that only about half of the students on average carried with them their electromagnetic waves textbook, though it was a required manual that, in most likelihood, everyone had a copy of. When asked informally about the reasons behind this situation, a number of students candidly replied that they very rarely needed their books in class because of the lecture format. Not carrying their books appeared to be an economy of space and energy.

With virtually no in-class problem-solving exercises taking place, students rarely needed their textbooks. The students' typical role in class actually consisted in taking down class notes from what the professor was explaining and/or writing on the board. They remained silent and seemingly attentive most of the time and only asked questions once in a while or whispered to one another on rare occasions. Overall, students' involvement generally appeared minimal and their passive role remained unchallenged.

A frequent pattern observed in the traditional lecture was that students would ask questions to the professor before class started. This was observed in seven of the thirteen classes observed. Upon arrival of the professor in the classroom, a few students would rapidly gather around him to pose questions to him. When these students were asked about their motivation to do so, they said that they simply found it convenient because this practice did not require any advance planning or appointment-making with the professor. If a question arose during their homework, study, or assignments, they simply made use of the minutes before the next class to sort it out. This approach seemed to be both convenient and effective as the professor diligently dealt with the students' questions. With three lectures per week, this approach provided a quick access to the professor without undue delay that would otherwise have prevented them from moving on in their study of the course content matter.

Some students also mentioned that they found this approach to be much less intimidating than asking a question during the regular class since only a small group of their peers could hear their questions and not the entire group. Discretion seemed to be another asset of this practice. The major inconvenience, however, remained the very limited time window provided. Often times, the students' questions could only be partially addressed within the few minutes available before class, if addressed at all.

When the number of congregated students was many, only two or three lucky ones got the chance to pose their question(s).

This tendency of students to pose questions to the professor before class also suggests that they are more active and comfortable in small groups. Moreover, it is possible that the proximity of the professor is reassuring. The impromptu and/or informal aspect of these short meetings with the professor, as opposed to a scheduled appointment in his office, might contribute to the apparent comfort the students display.

The Milieu

The Electromagnetic Waves classroom was situated in the Physics Department, as was the professor's office. The students consequently had easy access to both. The classroom could easily accommodate over 60 students. The chairs were detached from the tables but each table accommodated four (4) students. Two series of these large tables were aligned on each side of a central alley. Because of the extra seats, the students could spread out in the class and the room never felt crowded. The high ceiling also contributed to the overall impression of spaciousness.

There were windows on the left hand side (i.e., students' point of view) of the class and this ensured excellent light condition in the classroom. Given that all of the rows of tables were on the same level, the slightly elevated blackboard area (at the front of the class) facilitated visual access to the blackboard, especially for students seated in the last rows of the classroom. The blackboard was as wide as the room itself, giving a spacious area for the professor to write on. The room was also equipped with both a mobile overhead projector and a built-in data projector. However, none of these pieces of equipment were used during the observed classes. The professor used the blackboard exclusively and remained at the front of the classroom at all times.

The Teacher and his Teaching

In this section, a description of the professor's approach to teaching in his traditional lectures is portrayed. The data collected with the observation grid (Appendix N), as explained in Chapter 3, included the systematic count of some specific teaching techniques and instructional features during the classroom observations. They will support this description and be complemented by interview data with the professor.

Teaching techniques.

The summary table for the various teaching techniques (inspired by the "Grille d'observation sur les techniques d'enseignement" (Cabral et al., 1997)) is presented in Appendix TT. Each technique is summarized on a graph which presents the number of occurrence of the specific technique for each observation date (see Figure 5 to Figure 13). The average adequacy of the technique (effectiveness and relevance marked on a scale of one to three) for each date appears on the right-hand secondary Y axis.

The class often started abruptly with little or no introduction or lesson plan (a very brief plan was verbally laid out at the beginning of five classes out of thirteen different classroom observations). On rare occasions, a quick review of the recent conclusions was presented and a statement about where the course was heading was made, but this did not necessarily happen at the beginning of a class. There was no formal wrapping up at the end of the class; the class generally ended because there was no time left. Summaries were provided when the class was ready to move from one topic to another or when a significant step in the curriculum was accomplished and this again was not necessarily taking place at the end of a class. The beginning or the end of a class did not seem to serve as a divider whereas the content matter did.

The professor took on the entire responsibility of presenting the content matter. Mostly, he presented demonstrations and derivations of a mathematical nature of the concepts, principles and laws being studied. He used detailed notes and, as he explained in his interview, every concept, equation or derivation written on the board had been thought out and planned. With his carefully prepared personal notes, he was able to stop in case there was a question from a student or make a parenthetic comment on a side topic without being the least disturbed or lost in his chain of thought. If such instances arose, he simply went back to his notes and resumed his presentation. His presentations were very structured and he seemed to have a clear idea about where he was going and how much he wanted to cover in a specific class period. However, the teaching goals and the expected students' learning outcomes to attain were not made explicit either verbally or in writing.

The professor displayed comfort in his role as a lecturer. His voice projected well even to the very back of the class and had some variations in it so it was not too monotonic. He used a controlled pace and excellent pronunciation, making every word he uttered very clear. He systematically highlighted complex features in his presentations and got students' attention with sentences such as "Ok Everybody! Follow this carefully!", "You want to watch closely here!", "This is a bit tricky!", etc.

He kept the blackboard well organized and easy to read at all times. It was never cluttered and most of the time he divided it in sections with vertical lines. His handwriting could easily be read from the very back of the class. Typically, he wrote exactly what he said orally on the board, i.e., full and complete sentences including punctuation and articles. He never used short cuts or abbreviations. Important results and conclusions were put into boxes or highlighted with colored chalk. In his interview, he explained that this was his way to keep the pace bearable for the students. The time he took to write gave students enough time to write down their notes and the time he took to draw graphs gave students a chance to catch up. As he mentioned in the interview, this consideration was his primary reason for never using overheads or PowerPoint presentations as these, he felt, would tempt him to cover too much material too quickly.

He consistently wrote with white chalk on the blackboard. He also used colored chalks effectively when drawing sketches and graphs. His drawings were precise and rigorous. He made good use of perspective and could draw 3-D elements easily to help students to “see through”. There were between two and seventeen graphs per class and each had a specific function. When a graph could be useful for a period of time, it remained on the board for as long as necessary and, when the content lent itself to it, it was progressively completed as the lecture unfolded.

It can be noticed from Figure 5 below that schemas and graphs were generally of high quality, that is, they were both relevant and effective. Their number varied from one class to the other and there was no discernable or clear pattern. Graphs and schemas were particularly present in the global summary of the course on the last class of the semester and their atypically high number might explain the slightly lower average quality on that specific day (see April 7th in Figure 5). Otherwise, graphical representations and drawings constituted a positive and meaningful complement to the lectures.

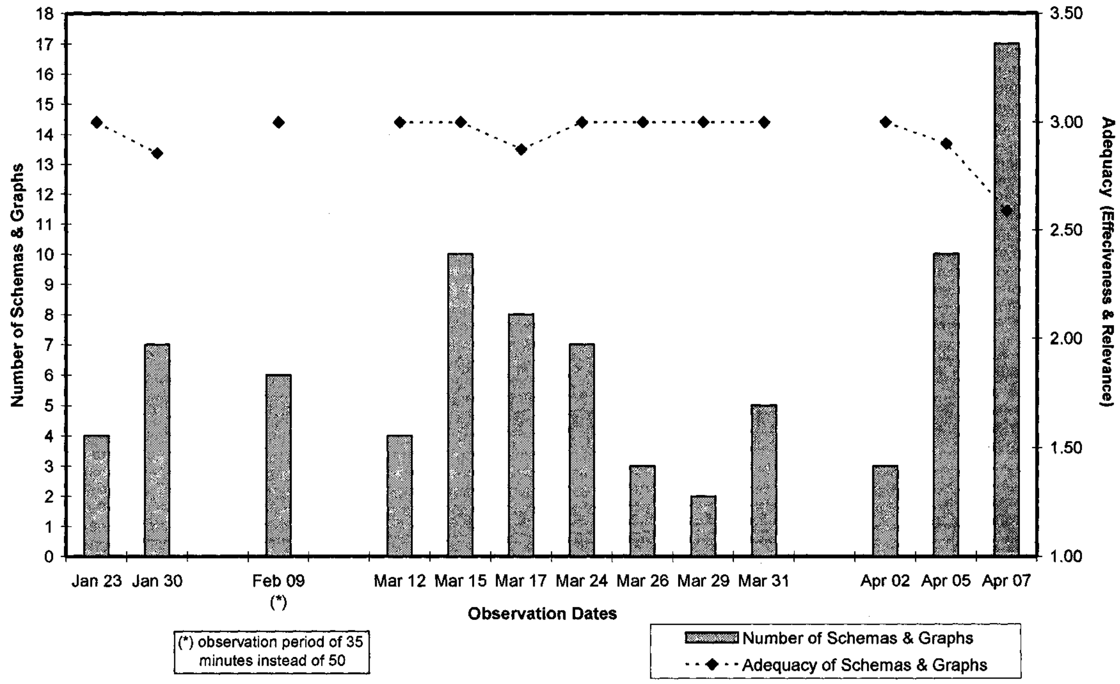

Figure 5. Drawing Schemas and Graphs on the Blackboard

The professor periodically checked the students’ understanding with phrases like: “Are you still with me?” (possibly the most frequent one), “Does everyone see that?”, “Can anybody see why I am doing this?”, etc. He often checked with students before erasing a large portion of the blackboard to make sure they were done with note making. He also often asked "All right?" but did not always wait for an answer before moving on.

From Figure 6 it can be seen that the professor generally provided students with enough time to answer his questions. His questions were of good quality most of the time. Some lower level questions, presenting a limited potential to foster students' thinking and understanding (e.g., those only referring to rote learning of facts or numbers), were rated with a smaller effectiveness score. It can be seen that on March 31st, corresponding to a complete class of worked examples and problem-solving, the professor was using questions particularly effectively. He actually used questions on that day to lead the students through the various problems reviewed in a very interactive manner. During more typical lectures, few questions were asked in general but they were effective and relevant. Toward the end of the semester, the pattern changed as time became an issue. Asking fewer questions to the class was possibly perceived as a means to save time and present more material, given the limited class time left to cover the course content.

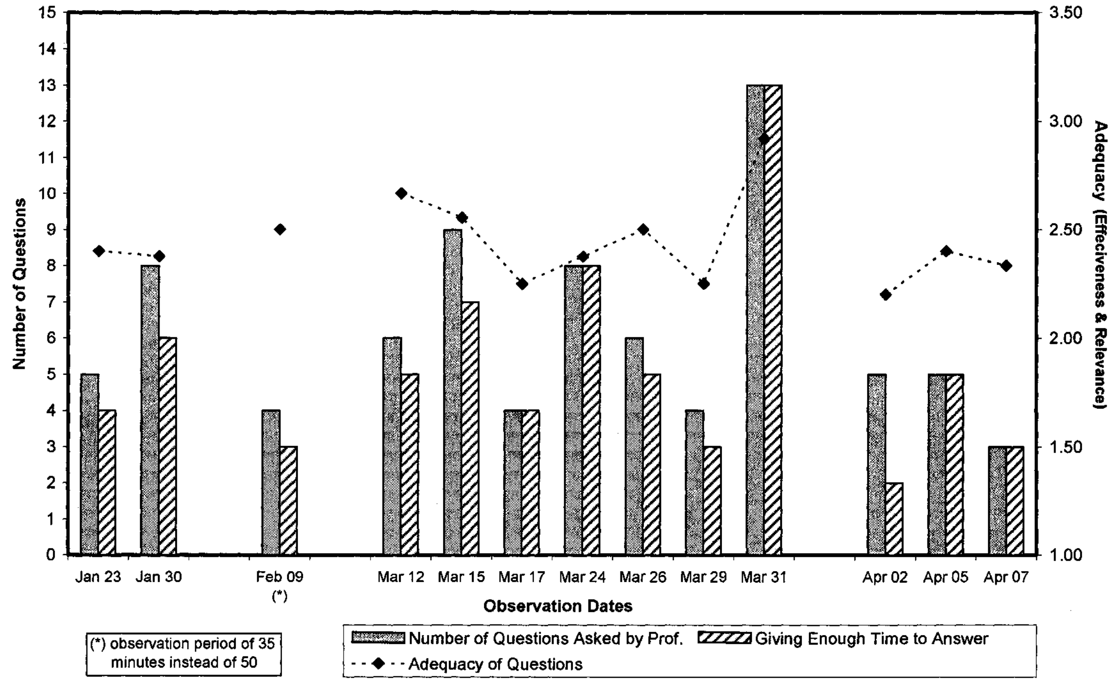

Figure 6. Asking Questions to Students

The professor also regularly invited students to ask questions and showed his openness to answering them. Questions from students were generally given a fair time and granted a detailed answer. However, when he seemed to be behind schedule, the lectures became compact and dense. On those occasions, he would temporarily stop to ask students whether they understood the concept. A real effort was made to refer to students' questions in his explanations (e.g., "One of you asked ..."), especially when some questions proved sound and articulate (e.g., "Ahh! Very good question indeed!"). All in all, he appeared receptive to questions and responded to them diligently.

There seemed to be fewer questions asked by the students toward the end of the semester (see Figure 7 below). The rapid pace of those last classes might have sent an indirect message to the students that it was not a good time to slow down the class pace with questions during such a busy period.

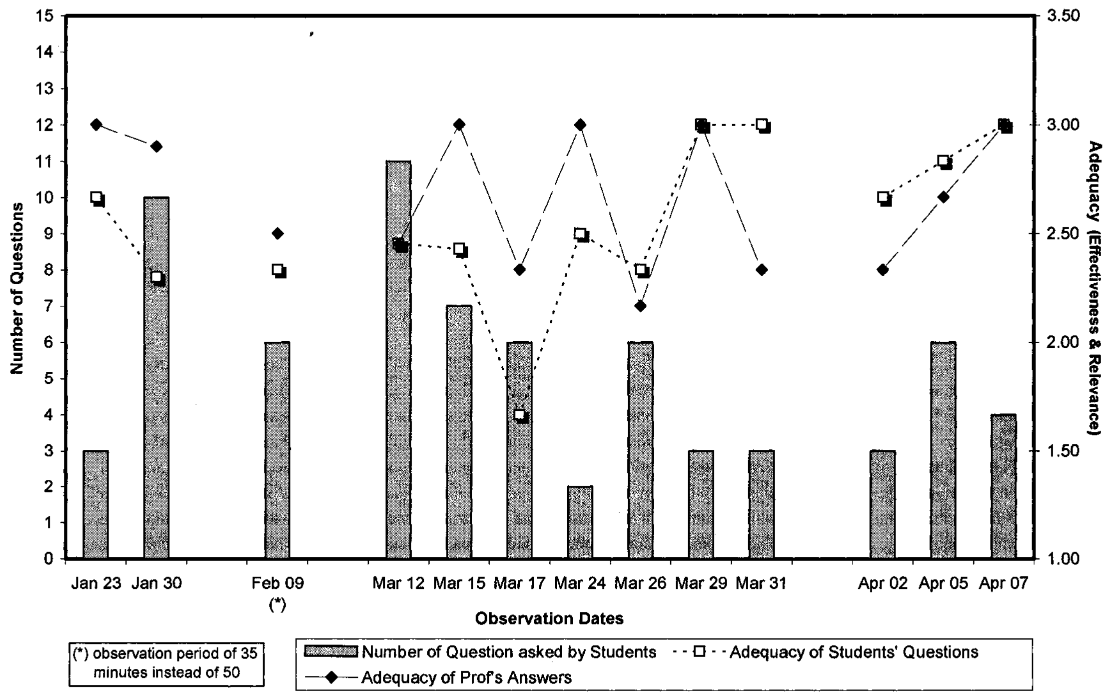

Figure 7. Questions Asked by Students

More likely, and presumably, the particularly dense lectures at the end of the semester did not provide students with enough time to really process the information which resulted in an apparent silence on the question front. It could be hypothesized that, in such circumstances and if students were indeed overwhelmed, understanding was postponed to a later moment and the in-class time was only dedicated to note-taking of the explanations and equations presented on the blackboard.

A very positive element emerged from this graph (Figure 7): the quality of the professor's answers was most of the time very high. On the few occasions when his answer was of limited relevance and effectiveness for the rest of the group, it was generally because the student's question itself was of a poor quality to begin with (e.g., lacking elaboration, focused on a detail, depicting an obvious lack of attention, etc.). This is suggested by the parallel fluctuations of the two doted lines on Figure 7 (i.e., respectively the adequacy of students' questions and adequacy of professor's answers) displaying the average quality scores for each observed session. This was also visible at the session level when looking at the numbers directly noted on the observation grids for each pair: a question asked by a student vs. the corresponding answer by professor. The quality of the answers made by the professor tended to match or surpass the quality of the questions posed by the students. In either case, the quality of the professor's answers fluctuated as a function of the quality of the students' questions. An excerpt (Figure 8) from the observation grid for Wednesday March 17th is presented below as an illustration. It can be noted that the rating of a student's questions (on the left-hand side) and the resulting answer of the professor (right-hand side) appear in corresponding cells on both sides. In other words, the first cell on the left in both panes (e.g., "1" for a student's question and "2" for the resulting professor's answer) pertain to the same question/answer pair.

Student(s) ask(s) Question(s) **Overall E&R**
1 2 3 1 1 2 ☐ ☐ ☐ ☐ 1 [✓ 2] 3
☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐

Answers Students' Questions **Overall E&R**
2 2 3 2 2 3 ☐ ☐ ☐ ☐ 1 [✓ 2] 3
☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐

Figure 8. Excerpt from the March 17 Observation Grid

The particularly poor questions were generally rapidly dismissed while good ones were answered in detail and even built on. Overall, the professor seemed receptive to most questions and made every effort to respond to them.

The professor rarely made mistakes on the board mainly because of his carefully prepared notes that he transferred line by line to the board. On the rare occasions when there was a mistake, he reacted well and seemed most appreciative if a student could locate and correct it. Though the pace was bearable in terms of note taking, it was often observed that this pace was still too fast for the students to process the information and to interact with the professor about it. The board kept filling up constantly from the beginning of the lecture to the end with little breathing room for the students to interject; this was especially true when new and unfamiliar material was introduced.

The professor introduced numerous examples of concrete applications (see Figure 9) as well as everyday life uses of the concepts and technologies he referred to, making his teaching more authentic and appealing to the students.

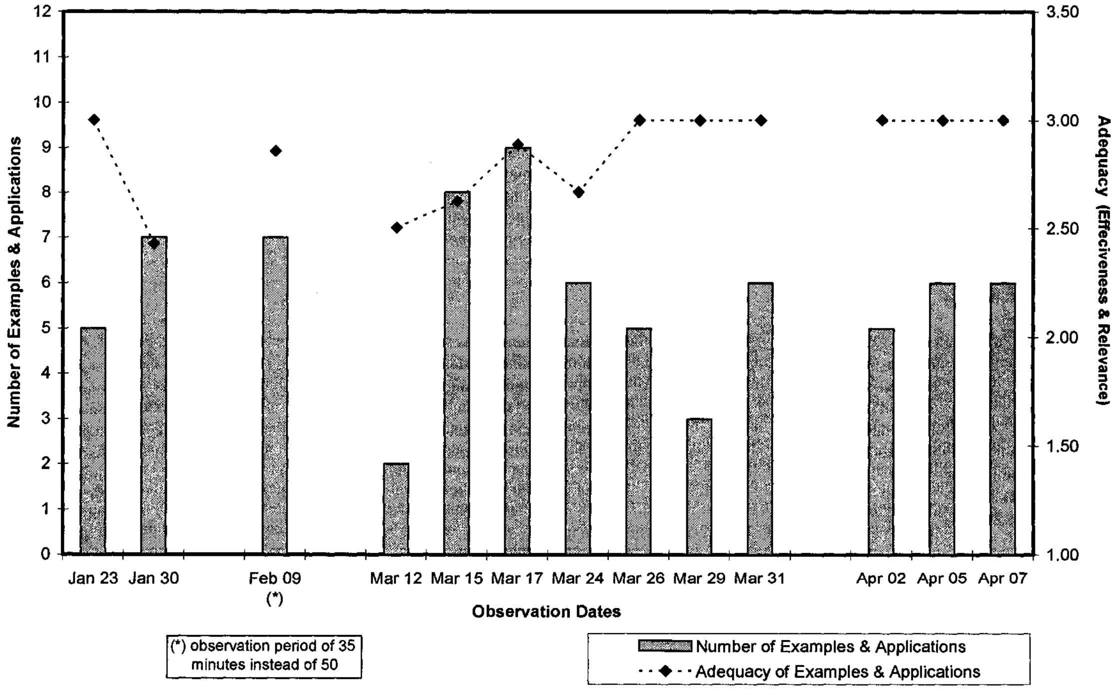

Figure 9. Providing Examples and Applications

As can be seen on Figure 9, the examples and applications were generally of excellent quality. They contributed to varying the range of stimuli offered in the lectures.

On one occasion, the professor brought sections of real waveguides and transmission lines for the students to examine what these "small" apparatus looked like when used in industrial contexts. The pieces were circulated in the classroom which, it could be observed, triggered the students' interest and even led to an exchange and questions from the students. The professor generally explained the "physical" meaning and implications of the concepts in his examples and often used gestures, when relevant, to illustrate his meaning better (e.g., gestures for depicting fields' propagation).

Analogies, too (see Figure 10), were consistently relevant and effective although they were used less often than examples and applications. Analogies were carefully detailed and presented in an intentional manner showing that they had been planned and were being introduced for a clear purpose.

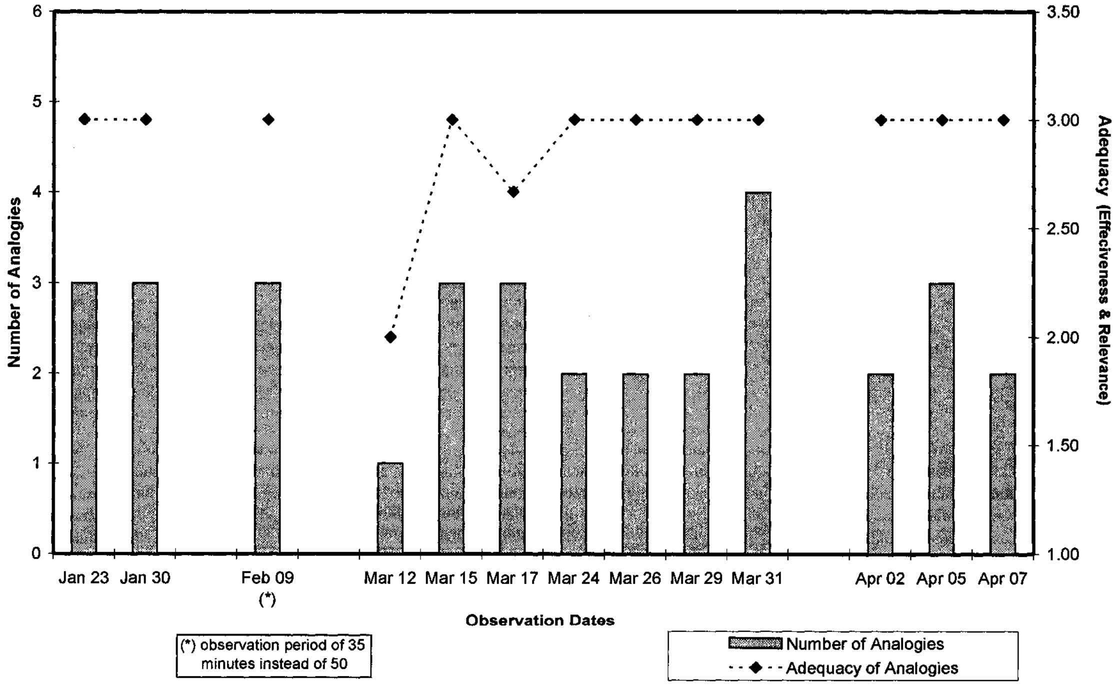

Figure 10. Using Analogies

The professor also periodically summarized a section or a topic with concluding comments and resulting equations that he wrote in full sentences on the blackboard. In this way, he wrapped up a series of lectures (or a portion of one), highlighted the essential features, and also provided the students with the appropriate vocabulary and correct way to describe a phenomenon. This was a concrete example of modeling how to draw conclusions and how to derive the core elements and defining features of complex theories or sets of equations. His summaries were exemplary from that perspective, always clean and comprehensive.

The professor used humor once in awhile and a few anecdotes to punctuate his speech. The anecdotes or humoristic comments (Figure 11) displayed a fluctuating quality, probably due to their spontaneous and unplanned nature. They, nonetheless, contributed to maintaining an open and pleasant climate in the classroom which seemed to be appreciated by the students.

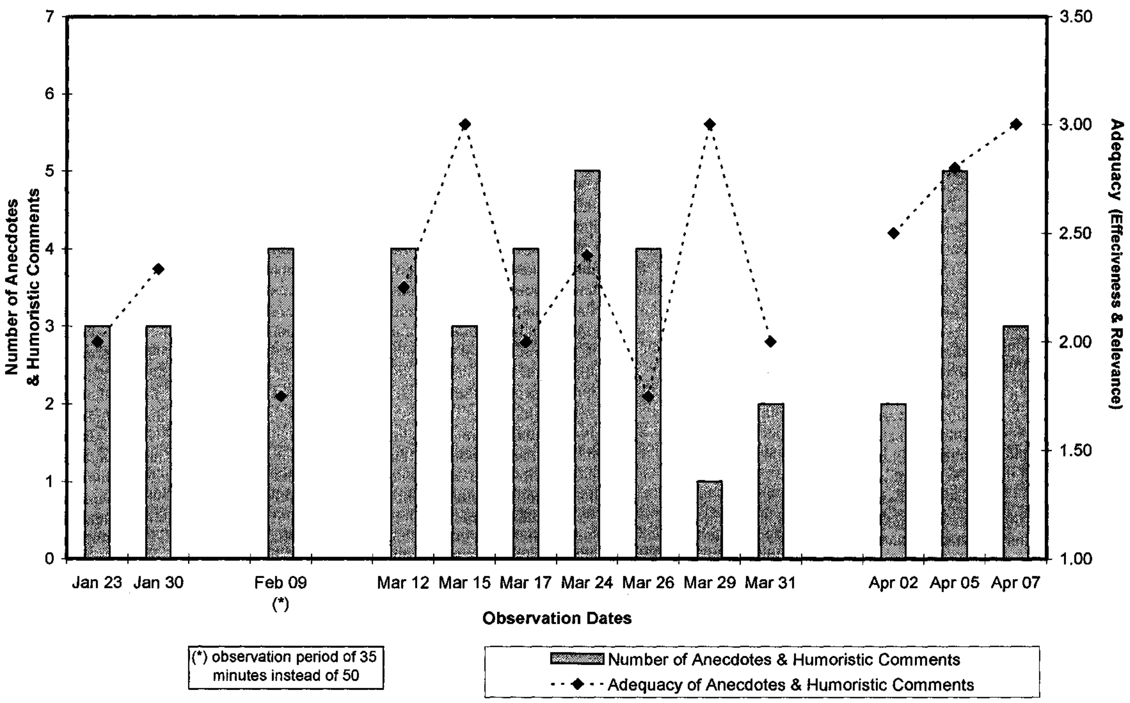

Figure 11. Using Anecdotes and Humoristic Comments

Two other teaching techniques observed also contributed to making visible the professor's experience and pedagogical content knowledge (Shulman, 1986). Modeling reasoning and problem-solving (Figure 12) and establishing links with prior knowledge (Figure 13) were two techniques that he used intentionally to give students a view of his own thinking and expert reasoning.

Although he did not have any formal training in university pedagogy, his extensive teaching experience and intrinsic interest for students' learning has enabled him to develop, over the years, a number of strategies specific to physics teaching that he found both effective and logical. He did not use the term 'modeling' per se when he described his intentions during the interview. He said he hoped that the students would develop similar reasoning capacities if they were exposed to his thinking out loud and making explicit the links between different concepts and courses.

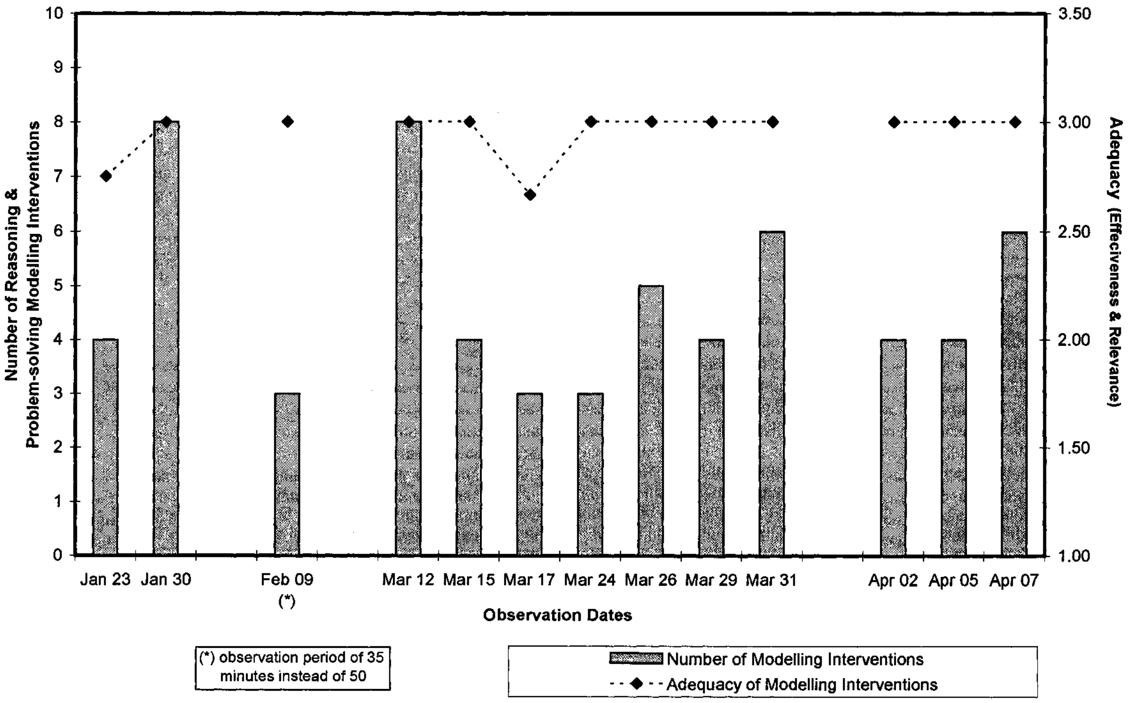

Figure 12. Modeling Reasoning and Problem-solving

The occasional worked examples (i.e., complete problem solutions) constituted a library of cases to which students could refer, observe similarities with, as well as build analogies from when dealing with unfamiliar problem-solving exercises in their weekly assignments. The worked examples were presented in a step-by-step manner and constituted good problem-solving modeling (Figure 12). The professor usually announced the steps he was going to go through and even showed contentment after a particularly tedious derivation or after obtaining elegant results. He often asked questions to himself as if reflecting out loud and sometimes asked a few questions to trigger students' reflection: "Anybody want to guess what is going to happen here?"

Links with prior knowledge (Figure 13), including links between concepts, between chapters of a course, and between courses themselves in the physics program seemed important to this professor. He often made them explicit in addition to encouraging the students to engage in that exercise as often as they could in all of their other courses.

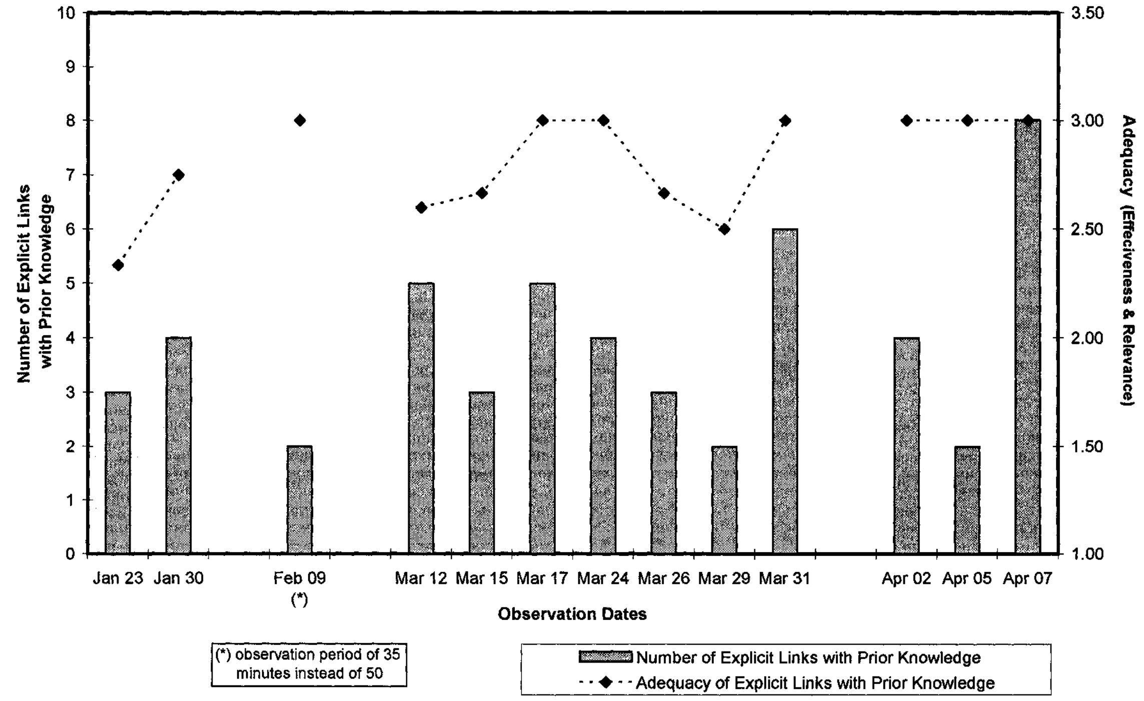

Figure 13. Making Explicit Links with Prior Knowledge

He also bridged from one concept to another with sentences such as "Remember what we said..." and related current material to already obtained results or previous demonstrations. He also sometimes inquired how many students were currently attending another course to which a specific concept would apply, making explicit what the link or relationship was.

Another type of interesting link occurred when he brought a historical perspective to his lectures and referred to fun facts; he seemed particularly knowledgeable about the history of science and he used this knowledge as an asset.

The professor emphasized the students' responsibility in connecting their physics courses together: "In physics you have to link things together more than in any other topics, if you have not already figured it out... though it is rarely apparent from most textbooks". From time to time he would say: "It is your job to relate it together", "I'll leave that to you to convince yourself", "Just like J.J. Thomson, physicists must think about the physics before writing equations. That's what physicists do!", "Mathematics is the language of physics, you need to get fluent in math", etc. He often mentioned additional references besides the assigned textbook.

The frequency of use of each of these last two techniques (modeling reasoning and problem-solving as well as explicit links with prior knowledge), particularly the modeling which requires time because of its very nature, seemed to depend more on available time during a specific class than on the content under study.

Instructional features.

The instructional features were adapted from Dona M. Kagan's (1990) *Configuration Checklist for evaluating a teaching performance*. The various features, specific to conceptual change, were rated in a scale of one to three, in terms of their degree of implementation, only when they were present during the observed class period.

Although the professor was clearly receptive to students' questions and even tried to encourage their participation, the course did not prove to be interactive (see the portion of Figure 14 pertaining to the 'Student role'). The students' in-class involvement was minimal throughout the semester and constituted mainly of note-taking activities. The assignments were good opportunities for students to reflect and develop a deep understanding of the material. However, they took place outside of the class and were directly associated with grades, rather than being a process for learning, limiting seriously the formative feedback that the students had access to. The heavy content load and the quick pace did not constitute conditions conducive to the active participation of the students. Figure 14 presents the graphical version of the result.

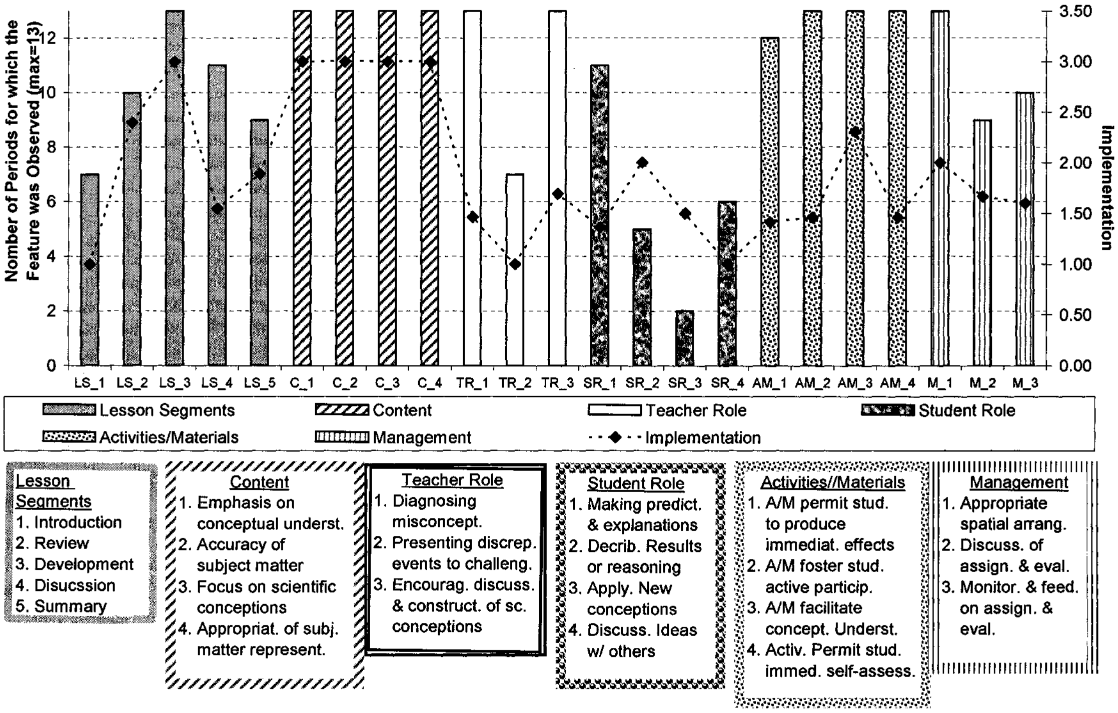

Figure 14. Instructional Features

A very strong feature, made apparent by the 'Content' related portion of Figure 14, is the expertise and comfort of the professor with the content knowledge involved in the course he was teaching. All features noted on the observation grid were systematically present in every class observed and the implementation was rated with the maximum number on the scale each time. His theoretical mastery was observed in class through his fluent articulation of the content, the clear and detailed format of all material presented, his ease in answering questions, and his comfort in providing complements of information as well as concrete applications.

PBL Context

The PBL activities that were developed in the context of this study had been designed to rapidly bring the participating students to function effectively in a PBL environment even if it was their very first experience with this instructional approach.

The Subject Matter

No introduction about the topics targeted in the PBL problem was provided to the students. The problem introduced had been carefully designed to be within students' reach, while being sufficiently challenging. The PBL problem asked the students to design a new waveguide for a microwave oven to be used in the International Space Station. A number of constraints were imposed on the allowed dimensions and substances to be used. The students were also asked to determine how big an aperture should be made in the cooking chamber to allow the astronauts the use of an infrared thermometer while preserving their security by maintaining a 99% shielding to prevent the unwanted leakage of microwaves.

Consequently, already studied and basic notions of propagation of electromagnetic waves in free space were helpful to some extent in approaching the problem and so were concepts such as transmission and reflection of waves from previous courses on optics. Notions that had just been addressed in class, about transmission lines, provided a background on which the students could build. The case of parallel plates had been introduced in class the day before. Essential notions such as cut-off frequencies, boundary conditions at the wall, attenuation, or transverse modes of propagation (TE, TM, and TEM modes) were new vocabulary terms rather than understood or integrated concepts, for the PBL participants. The specific case of propagation of electromagnetic waves inside of rectangular waveguides (either hollow or filled with a dielectric) that was going to be at the very heart of the PBL problem had not yet been addressed in class.

Other aspects of the problem were completely foreign to the students. While most students had used a microwave oven numerous time before, to either heat or cook food, none of them was familiar with its functioning or basic components. The problem led the students to develop a clearer understanding of the functioning of the magnetron, including the frequency and fluctuations of the microwaves it emits and the nature of its coupling with the cooking chamber via a waveguide. The problem also forced students to question a number of misconceptions they had about microwave ovens and microwaves in general, particularly in terms of security issues, including shielding notions, when debating which materials transmitted or reflected microwaves (e.g., the glass door vs. the metal wire mesh that covers the glass).

The Learners

The four PBL students were males in their second year of undergraduate physics, enrolled in the major's Electromagnetic Waves course. They had volunteered to participate in all of the PBL-related activities taking place over a period of one week, in the context of this study. In their regular class, they usually sat at a good distance from each other. None of them was the lab partner of any of the other three participants. From the classroom observations, there was no indication that these students even spoke to each other at any time, including when arriving or leaving the classroom. In their interview, they said they knew each other's name, since they were in the same cohort, but they did not report having any other personal knowledge of each other prior to the PBL activities. The researcher was interested in how, as a group, they engaged in an unfamiliar and demanding task and in what way the group dynamic facilitated the process.

The strengths and natural learning style of each student became apparent within minutes after the beginning of the first PBL session and set the tone in defining each student's role in the group. These individual approaches and roles remained very stable over the course of the week, both during the tutored session as well as during the students' meeting.

From the beginning, Student-1 had taken upon himself to be the scribe of the group and his role remained unchallenged. He had a "theoretical" approach to concepts and seemed to always be able to summarize whatever he knew or remembered about a specific concept or theory. He appeared to be vocal mostly when a conceptual summary or theoretical explanation was needed. Otherwise he did not seem particularly prone to thinking out loud or formulating tentative hypotheses. He spoke in a very clear and articulate fashion when he was sure of what he was about to say and his evident, almost textbook-style, theoretical knowledge proved useful to bring the group back on track on a number of occasions. He also had a very precise and systematic way of using equations in relating concepts together and in performing calculations. He was very effective in gathering specific facts and explanations to advance group work.

Student-2 was the most extraverted of the four. He was not the least bothered by the video-camera and used his hands when he talked. He spontaneously took the lead during brainstorming sessions. He did not hesitate to voice out tentative ideas or provocative questions. He had a natural ability for thinking out loud and monitoring his own verbal comments whenever they were not robust enough. He used complete and elaborated sentences even when playing with uncertain thoughts. His knowledge appeared to be intuitive and he often referred to his personal experience to elaborate on issues. He easily played with abstract concepts and relationships but could rarely refer accurately to specific laws or equations. He, admittedly, said that he did not try to memorize formulas, names or constants. Rather, he tried to get the big picture and often drew on his knowledge from various past and current courses in the physics program to support his reasoning. He was not the least offended when one of his ideas was dismissed. He was a real team player and often directly prompted the others to offer their perspectives, making sure that everybody had a chance to voice their ideas.

Student-3 was the meticulous hard-worker of the group. He systematically verified every fact, number, theory, formalism, and principle behind the problem. He was excellent in formulating the fundamental questions the group needed to ask and often contributed to articulating the learning issues they needed to address. He appeared very humble when expressing his understanding of things, often underestimating the extent of his knowledge or expressing a lack of confidence in his reasoning, even though he was often right. He was actually the one who figured out the logarithmic relationship needed to address the shielding sub-problem and consequently successfully completing their task. He felt most comfortable surrounded with books, research articles, and handbooks. He carried them everywhere with him at all times and was always looking for additional and trustworthy references. His pace was a bit slower than that of the others. However, each time he reported his findings to the group, every piece of work he had prepared was exact and detailed. He liked elaborated graphs and drawings as they conveyed explicit meaning.

Student-4 seemed to be the most quiet and reserved of the four PBL participants. He was particularly uncomfortable with the video-camera and was visibly more relaxed and surprisingly vocal and interactive during the students' meeting, the activity which was not video-taped. Student-4 was excellent in wrapping up and summarizing the group's progress. He informally took upon himself the role of time-keeper, always making sure they were on task and progressing in a satisfactory manner. When necessary, he would remind the group what they still needed to accomplish. He rarely took a chance on unsure suggestions but was most of the time the quickest to realize that they had ventured into an erroneous path. He was very diplomatic in his interventions, especially when correcting someone else's reasoning or opinions. He never cut off anybody's speech and spoke in a soft way. He, nonetheless, had no difficulty in getting complete attention whenever he intervened.

It is impossible to predict how the group dynamics would have evolved, or if conflicts would have eventually arisen, had the PBL activities been spread over the course of a complete semester, for instance. This is not uncommon in PBL contexts. But, during the week-long period of this study, these four students worked together efficiently and complemented each other. They successfully solved the problem as a group and each of them contributed significantly to the positive outcome. They had obviously understood from the tutor's introduction to PBL that they needed to be active and self-directed learners and that nobody was going to provide them with ready-to-use answers but they would not be abandoned in the face of a dead end. They welcomed any intervention by the tutor but never turned to him for assistance or asked him any direct questions. They simply persevered and continued their discussions, relying on one another.

The Milieu

The PBL activities took place within the Physics Department, in a regular classroom the students were familiar with. This room had desk spaces and chairs as well as blackboards where the students could easily put up the flip chart sheets. The only unusual component of the classroom setting, at least during the two tutored PBL sessions, was the presence of a video-camera. The researcher used flat microphones to capture the sound and allow for a distant video-taping in an effort to minimize the discomfort for the students while preserving the quality of the data.

The Tutor and his Tutoring

The PBL tutor was not extensively observed in his natural setting in the way the professor of the Electromagnetic Waves class was. The PBL sessions were two hours long each. Moreover, the observation grid used for the traditional teaching would not have been appropriate to describe or report on the interventions of a tutor in a PBL setting because PBL is by definition designed around the students' active involvement, not around the tutor's teaching acts.

The tutoring strategies used by the PBL tutor were nonetheless coded using the verbatim transcription of the two tutored sessions. The results pertaining to the occurrences and context of utilization of each strategy are presented in the fourth section of the present chapter. What is offered here is a brief description of the tutored PBL sessions themselves.

First PBL session.

Before the actual first tutored PBL session, the students were presented with a one hour introductory interactive lecture on the PBL approach and group learning. It is to be noted that the students were not assumed to know anything about PBL prior to their involvement in the research. The students' potential prior knowledge on the topic was verified by the tutor at the beginning of the introductory lecture: the participants had actually no prior knowledge of such an instructional approach, of its historical roots, related terminology, or guiding principles.

The first PBL session began with a brief recapitulation (about the PBL approach to problem-solving and students' role when working in groups) at the end of which, the Spatial Microwave problem especially designed for this study was introduced to the students. No explanation or theoretical information was provided to the students even though the problem was challenging and clearly beyond the students' existing knowledge level.

Students were invited to use the 4-column method explained to them in the introductory lecture to identify a) Ideas (what spontaneously came to mind when reading this problem, what it seemed to relate to, or what initial ideas they wanted to note in order not to forget them later on, etc.), b) Facts (what they were told in the statement of the problem, what factual information was clearly stated or constituted facts they could count on, etc.), c) Learning Issues (gaps in their current knowledge, missing information from the problem statement, anything they would need to investigate or figure out, etc.), and d) Tasks (things to do, plan of action, division of tasks among the team member, etc.). Because the problem included a number of not yet studied concepts (e.g., waveguides) and implied an understanding of the properties and functioning of microwave ovens that the students clearly did not have, most of the first session was spent debating the learning issues. Students used their textbook to initiate their information gathering and weighed many hypotheses.

During this first session, the tutor mainly intervened to give procedural guidance to the students (e.g., "Why don't we explore just that? I mean what you already know.", "How would you state the problem?") because they were not familiar with the PBL approach and, as a result, tended to go in many directions at once. Via a few short interventions, the tutor suggested ways in which the students could organize their work (e.g., "Again, on a first page you can have your ideas. You can use the pages here and rip it off when you are ready to stick it up here.", "Your learning issues are what you need to learn. And beside each learning issue you might want to write a name."), including a clear organization of the tasks and responsibilities (e.g., "Just try … for 10 minutes. Think about it. Ask each other questions. See exactly what you understand.", "Time is running low and I suggest that you clarify now who is responsible for what before we wrap up").

The tutor intervened very rarely in relationship to the context and when he did it was to either ask a leading question or to give a hint (e.g., "Why is that? Why are they not using open bowls?", "What makes the walls absorb or reflect?", "How can you control this angle with the microwaves bouncing off the sides?", "How do you decide on the size of the hole?"); never to give a direct answer.

As it had been suggested to them, the students concluded the first PBL session with the planning of what was to be accomplished, their goals, and how to approach the problem. They also decided who was going to research what topic and thus divided the tasks in preparation for their student meeting.

Student meeting.

This meeting was only one hour long and occurred without the presence of the tutor. Students took the opportunity to touch base, report on and share what they had been responsible for documenting. Student-1, the group scribe, wrote down every bit of information and steps the group engaged in during this student meeting. Because of the quality and comprehensiveness of the information that they had been able to gather, the group was ready to tackle some aspects of the problem and successfully deal with the waveguide sub-problem. Students also refined their list of learning issues, mostly pertaining to the shielding sub-problem. And, once again, they divided the tasks that each of them was going to be responsible for in preparation for the second tutored PBL session.

Second PBL session.

The second tutored PBL session began with a summary provided by Student-2. This concerned their progress and accomplishments to date. It served as a good basis for their own work and also brought the tutor up to date since he had not been present during the student only meeting. Each student also reported on the tasks they were responsible for. The students progressed in their problem-solving actively for about forty-five minutes at which point it became evident that they were not going to be able to deal alone with the calculation of the shielding effectiveness. They needed additional support from the tutor. Anticipating this outcome, the researcher and the tutor had prepared an information document which was handed over to the students at this time. With this new source of information on shielding and on how to calculate it, the students engaged in the final phase of the shielding sub-problem. The logarithmic scale implied by the decibels proved challenging but the students were able to figure it out and to successfully calculate the size of the aperture that could safely be drilled in the cooking chamber of the microwave oven. Once again, the tutor's interventions were limited to situations where the students had reached a dead end. Whenever they were progressing, he refrained from any intervention that would have led them specifically. He mostly used hints and questions to guide their work. (e.g., "So let's just even take it back and simplify. You're saying that the hole's smaller than the wavelength?", "You know that gives you also another option right?", "What's the log of…"). When the students had reached a result, even an intermediary one (e.g., Stud3: "There's just got to be somewhere where we would have actually log scales instead of formulas", Stud2: "One twentieth of the wavelength that's better."), the tutor provided evaluative remarks to confirm the exactness of the answer and to inform the students about their level of advancement (e.g., "Very good! Ok!", "Right.", "Excellent!", "Well you did very well!").

Overall, the tutor was an attentive observer of the students' work. He was able to refrain from intervening and could tolerate and modulate the students' level of discomfort. As long as the students were progressing, the tutor generally refrained from any intervention, allowing the students to work at their own pace. In the face of a dead end (e.g., the inability of the students to determine how to calculate the shielding effectiveness – a concept clearly more advanced than their level) and given the fact that the second session was also the last the students had to complete their problem, he strategically chose to intervene and provide essential information (i.e., the actual shielding effectiveness formula along with logarithmic graphs illustrating it). He then left it up to the students to understand and make use of this written information (e.g., "Since this is your last session, here's some information about the shielding effectiveness of apertures. If one of you can just read this in front of the group.") This information could not have been derived by the students and they had not been successful in locating it during their self-directed study. Without this vital piece of information, it would have been almost impossible to successfully complete the solution to the problem. Nonetheless, the material provided did not lead the students directly to the answer. They were not familiar with logarithms and they needed to understand as a group how they could use the shielding effectiveness formula to calculate the size of the appropriate aperture in their context.

Instructors' Perception on Teaching and Learning in Physics

The results presented in this section were derived from the thematic analysis of the verbatim transcription of the interview with both the professor and the PBL tutor who participated in this study. Samuelowicz and Bain's (2001) framework helped organize the emerging perceptions, given each instructor's respective instructional approach, and helped compare and contrast them systematically. Table 34 summarizes the findings for the "Desired Learning Outcomes" and the "Expected Use of Knowledge" dimensions.

Table 34
Desired Learning Outcomes and Expected Use of Knowledge

Dimension	Traditional Teaching Professor	PBL Tutor
Desired Learning Outcomes <u>Students should:</u>	• become self-directed • "have a picture" (i.e., get the big picture and go beyond algebraic representation) and "see physics as a whole instead of isolated things. Everything connects together and is related to the environment around them." • "be creative" and able to deal with new problem • become able to approximate realistic ranges of answers ("it's the most sophisticated thing they learn to do... one of the most critical skills and that does not come easily") and utilize "critical thinking in doing so." • be able to criticize other people's work and thinking ("Don't be sorry to criticize what other people have written... it's important to challenge <u>authority</u> otherwise you won't make it here.")	• be autonomous learners ("know whereto go to learn") and be able to determine "what you know and what you do not know and how to apply what you know".) • develop a self-evaluating attitude and "monitor everything they do" • "deal with a situation you have never seen before." • have a "strong knowledge basis" • develop "good problem-solving abilities" • become able to identify "very realistic assumptions" • develop critical thinking "when there is too much information and when there is not enough information"
Expected Use of Knowledge	• students should be able to ask "penetrating questions" to inform prof about their difficulties and "think along" with the professor to show their reasoning • relate things together	• active use and application ("apply conceptual understanding and knowledge to solve problems" • strategic use depending on the context • "I want them to have a good understanding of the scientific process, to apply it...and to do research that's quantitative"

Both the traditional professor and the PBL tutor interviewed wanted their students to become self-directed and autonomous, to develop critical thinking and be able to make realistic approximations. Table 35 presents the findings for the "Professor's Responsibility for Organizing or Transforming Knowledge" and "Nature of Knowledge" dimensions.

Table 35
Professor's Responsibility and Nature of Knowledge

Dimension	Traditional Teaching Professor	PBL Tutor
Professor's Responsibility for Organizing or Transforming Knowledge	• know how to use the blackboard and clearly organize material in a coherent way • know how much can be covered in a course and in what order • choose textbook and be comfortable to reorganize the material • evaluate students' learning • be prepared with really detailed lecture notes "everything is written out"; profs' notes are a refined product • present material ("you have to get the concepts across by endless repetitions of examples, explanations, pictures." • link concepts with those of other courses ("I set them problems where they have to go back and use techniques and knowledge from earlier courses." • keep students updated with "new developments and new applications" in the domain • share course material with new profs when you are experienced ("you know this is a lifetime collecting good problems")	• get "personal training into good PBL tutoring" • set the students' learning outcomes ("skills and knowledge") • ensure access to appropriate resources • be responsible for some aspects of evaluation and share others with students • model the problem-solving and PBL process for students ("Tutors giving tutorials… and think aloud so they can see all the steps that go through your mind … the tutor solve the problem in front of them." • "train new profs for PBL using PBL"
Nature of Knowledge	• "abstract" and "conceptually challenging" • "linked to everyday life"	• "constructed"

The traditional instructor took on a large responsibility for presenting the knowledge in a detailed, clear, and well organized manner. It was his responsibility to be a good and effective communicator in charge of the students' learning. He counted primarily on his expertise both as a physicist and a professor to teach well. He was also solely responsible for the evaluation of the learning.

The PBL tutor felt it was important to inform the students about the learning outcomes he had designed for them and to make sure that they would have access to appropriate resources to discover themselves what the relevant knowledge and concepts were. His approach was student-centered and he and the students shared responsibilities in the learning process, including evaluation (which often took the form of oral presentations).

Both instructors acknowledged their responsibility in being qualified and well prepared for their teaching. It is also interesting to note that both instructors also felt a responsibility in facilitating the professional acculturation of their colleagues via the use of the very teaching approach they themselves use regularly and feel comfortable with. For the traditional instructor, the sharing of detailed personal notes, refined over time, with new faculty was one of the most effective ways to help less experienced colleagues. This approach appears very similar to giving a structured lecture: the experienced person provides the instruction and the novice receives it, more or less passively.

The PBL tutor teaches PBL to new staff using PBL to make sure that future tutors experience both sides of this instructional context (i.e., as students and as tutors). In both cases, the instructors tended to systematically reproduce their most familiar and comfortable mode of teaching with new colleagues as well as with students. Both instructors found it sometimes challenging to "convince" colleagues of the importance of their dedicated approach to teaching and both used the term "laziness" to describe the attitude of some colleagues who are not so passionate about teaching.

Table 36 displays the very similar views of the two instructors on students' conceptions and misconceptions.

Table 36

Students' Existing Conceptions

Dimension	Traditional Teaching Professor	PBL Tutor
Students' existing conceptions	• many misconceptions exist and prof needs to be aware of them	• many misconceptions exist and tutor needs to be aware of them ("the challenge is that whatever way you're teaching, the students need to actually be forced to confront the misconceptions they have, see whether or not they are correct and build up a concept understanding that is correct.", "I need to develop good problems that will address all of their misconceptions")

Table 37 presents the comparison of the two interviews for the last four dimensions considered.

Table 37

Interactions, Control of Content, Professional Development, and Motivation

Dimension	Traditional Teaching Professor	PBL Tutor
Teacher-student interaction	• teacher is provider of information and student is receiver • students ask questions during lectures • students evaluations of teaching are important for profs' improvement • prof can "tickle" the students' minds and provide context for complex learning	• prof needs to refrain from intervening • profs needs to tolerate students confusion and frustration ("step back and let them get confused", "students learn a lot by working through their confusion") • partnership ("we are both active in the learning process", "if the student does <u>not</u> participate in the learning process then I don't believe it is a <u>worthwhile</u> process") • "meetings with the teacher should be more a facilitation of the learning process" • friendly: ("I don't like this power relationship...my students and I are friendly", "That's all part of the social congruence... making students comfortable in a learning environment is very important.")
Control of content	• prof's experience guides him in selecting content and textbook	• shared with students and varying with projects and problems
Students' professional development	• "you need to sweat it" to become a good physicist (i.e., to work hard and to figure things out by yourself)	• done through experiencing all aspects of research (even at the bachelor's level)

Interest and motivation	• teacher initiated by selection of real life applications • teacher initiated: by showing that "there is a value to understanding" • teacher initiated: through grades • teacher initiated: by being approachable and available for students, sympathetic, calm and clear in his teaching	• PBL is the motivation ("one of the things with PBL is that it motivates students in itself.") • Students' personal interest are taken into account in projects and problems

The professor clearly indicated that he was the one disseminating the knowledge. He controlled the pace and the content while also being responsible for the students' motivation. His experience helped him to select the most appropriate content and textbooks for his students. He also explained that the students had to put in a lot of conscientious effort to learn physics and that there was no other way to achieve results that he knew of. It is to be noted that he found the students' assessment to be one of the most important and significant sources of information for faculty interested in improving the quality of their teaching.

In the PBL approach, in contrast, the tutor placed more responsibility in the students' hands, providing little guidance and tolerating confusion among students yet facilitating the learning process during meetings. The PBL students, he explained, are responsible for researching the contents themselves and the tutor has to be ready to assist them and adjust to any direction they might head to.

The PBL tutor who was interviewed in the context of this study believed that teaching and learning should happen at the same time and that good PBL tutors needed to easily resist the urge to provide students with ready-to-use answers. The personal interests of the students as well as the PBL format itself are expected to nurture the students' motivation.

The PBL tutor recognized the effectiveness of lectures in developing a strong knowledge base but insisted on the need for students to practice applying their knowledge and developing new skills in a supportive and safe environment, composed of peers before any evaluation was attempted. The PBL tutor insisted on the importance of being "very transparent with all of the learning outcomes for the course and even for a specific class… even the assessment criteria". He used the term "alignment matrix" to describe how the objectives and the formative and summative assessments were articulated together.

Summary about the Instructional Contexts

The traditional instructional context that prevailed during the observed "Electromagnetic Waves" classes was typical of other courses in physics that are led by experienced physicists/professors who are comfortable with lecturing. Despite the professor's openness to students' questions combined with his diligent answers both before and during class, overall, the format simply was not conducive to sustained interaction with students. The professor was the main actor and he was in charge of disseminating the content matter. He was also solely responsible for evaluation and used traditional summative evaluations (i.e., weekly assignments and exams) to assess students' understanding. In class, the students remained relatively passive in their role. Most of the time, they silently transcribed what was written or presented on the blackboard. The pace often appeared too fast for them to really digest the concepts during class time or to ask integrative questions.

Nonetheless, these lectures were effective in more ways than one. They included many of the qualities required of a "good lecture" as described in the literature (e.g., Frederick, 1986; McKeachie, 1999; Saroyan, 2000; Saroyan & Snell, 1997). This professor's mastery of the content knowledge and his ability to articulate expressions of the complex concepts were robust aspects of his teaching. His use of relevant analogies, examples and other forms of effective representations revealed his pedagogical content knowledge (Shulman, 1986) despite his lack of formal training in university pedagogy.

He had a good understanding of the students' typical conceptual difficulties based on his years of experience in teaching physics. During particularly complex demonstrations and as a part of worked examples (Atkinson, Derry, Renkl, & Wortham, 2000), this professor usually announced what difficulties might arise or which potential caveats should be avoided when using the resulting equations. He modeled out loud his reasoning as he went along, giving the students opportunity to be exposed to expert thinking and problem-solving.

The PBL context could not be studied in as much detail as the traditional approach because of the short period of time allotted for the PBL intervention. Nonetheless, during the two tutored sessions, most of the PBL defining principles were observed. Similarly to van Kampen et al.'s (2004) experiment which implemented a single physics module through PBL teaching into a lecture-based curriculum, the PBL problem presented to the students was slightly more contained or structured than in a “pure” PBL context. In this study, the PBL problem had to be solvable within a week. The microwave problem presented to the PBL students was nonetheless challenging and it constituted the main focus for learning. Limited information was provided to the students and, to arrive at a solution, the students had to identify and research themselves the necessary information.

As indicated in his interview, the tutor used an approach to tutoring very similar to his usual PBL teaching, i.e., he intervened in an intentional and controlled manner, only when he felt that the students were facing a dead end. His interventions took the form of questions or hints most of the time. Whenever the students were progressing, even slowly, he refrained from intervening directly or providing information as he could gauge occasional frustration or need of assistance of the students. It was observed, and addressed with the students at the end of the intervention that, rather than being frustrating for the students, this approach had actually empowered them. The students indicated that they were proud of themselves for they had solved a difficult problem with minimal assistance.

Between the PBL sessions, the students engaged in self-directed study and were each responsible for documenting specific aspects of the problem and subsequently sharing their findings with the rest of the group. Maybe partly due to the short period of exposition to this instructional context, the PBL students did not appear to experience what is documented as a frequent potential source of conflict within groups learning collaboratively, i.e., the unequal student investment (Bennett & Osana, 2001). The workload seemed allocated fairly among the four participants and they worked as a team in what appeared to be a supportive and positive ambiance throughout the week.

Cognitive Abilities when Solving Problems

For the third research question, concerning the students' metacognition, critical thinking, physical intuition, and general problems-solving abilities when they solve advanced electromagnetism problems, the students' notebooks constituted the main source of data. All written plans and solutions to the two problem sets (pre- and post-tests) composed the data corpus. Both the presence and quality of the various cognitive processes and problem-solving abilities under investigation were systematically coded.

Nineteen students did the pre-test while fourteen completed the post-test. Twelve students completed both the pre- and the post-test which implies that the thirty-three resulting problem sets (19 pre- and 14 post-tests) were actually filled by twenty-one distinct individuals. Figure 15 presents the number and gender of the participants for the pre- and post-tests in the form of a Venn Diagram.

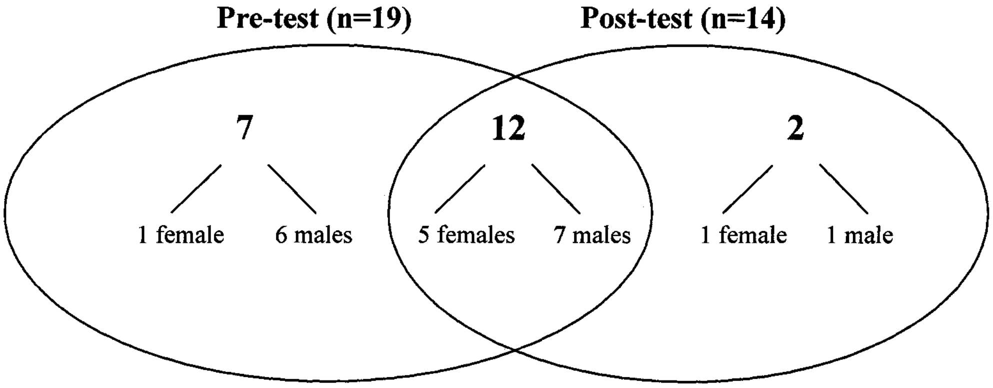

Figure 15. Participation to Pre- and Post-tests

A Priori Hypotheses

Three (3) *a priori* hypotheses were formulated in regard to this source of data. The first *a priori* hypothesis consisted in expecting no differences in the pre-test between the traditional teaching students and those who subsequently participated in the PBL activities. At the time of the pre-test, no student had been exposed to anything but their regular teaching context. Differences favouring the PBL students (e.g., significantly higher metacognition, critical thinking, physical intuition, or problem-solving scores) in the pre-test, for example, could have suggested that the PBL students were somehow not representative of the students in their cohort. This could have then implied that the PBL students were, from the start, stronger than their peers in terms of their cognitive processes or problem-solving abilities and the sample, because of self-selection, was consequently biased.

However, the PBL students did not turn out to be different from their peers in the pre-test. A planned comparison via a multivariate analysis of variance was performed to compare the overall metacognition, critical thinking, physical intuition, and problem-solving scores of the traditional teaching students with those of the PBL students. The main effect of the group status (i.e., being in the traditional teaching subgroup or being a future PBL participant) was not significant (p= .568) (see Appendix UU for the complete table of results). Appendix VV shows that no significant differences were observed in the pre-test between the PBL and the traditional teaching students for any of the specific cognitive abilities either.

Given that the PBL students were no different in the pre-test than their peers, various explanations could be forwarded to explain why these specific students eventually volunteered to be participants in the PBL activities but their cognitive abilities, as assessed in the pre-test, do not seem to be the motivating factor.

From the results of the pre-test, a corollary to the first *a priori* hypothesis followed: in the event of the PBL activities not producing any impact on the PBL participants, all students (regardless of whether they participated in the PBL activities or not) should evolve in time, should there be a change, in a similar way and also obtain similar results in the post-test. In other words, if all participants were equal after the pre-test, potential differences in the post-test between the two groups (traditional and PBL students) could more easily be associated with the consequences of the treatment (in this case, the PBL activities) that only the PBL students had been exposed to, between the two assessments.

The second and the third *a priori* hypotheses had both been articulated specifically to address potential differences between the pre- and post-test of each group of students (traditional vs. PBL).

The second *a priori* hypothesis was phrased in the following manner: given the stability of the traditional instructional context and the limited period of time (18 days) between the pre- and post-test, no significant differences were expected to be found between the two tests of the students in the traditional instruction group, for any of the measured cognitive abilities indices. The third *a priori* hypothesis pertained to the PBL students: a difference between the pre- and post-tests was expected either for a) the metacognitive index (because of the stimulation of metacognitive skills in the PBL intervention) or b) the physical intuition index (pertaining specifically to the second problem of each problem set, because of its unfamiliar nature). In other words, the PBL activities were expected to stimulate the students' metacognition and self-questioning habits as well as to help the PBL participants gain confidence in their ability to deal with unfamiliar problems. Consequently, resulting improvements in either or both of these specific indices (significant or not) were expected among the PBL students.

Results indicated that the third *a priori* hypothesis was verified: there was an improvement in the physical intuition indicators of the PBL students in the post-test. However, the second *a priori* hypothesis could not be validated: significant changes from pre- to post-test were unexpectedly observed for the traditional teaching participants. Interestingly though, they are not the same as for the PBL students (i.e., not related to physical intuition). The two subgroups (i.e., traditional and PBL students) did evolve in time, but in different ways. These distinctions between the pre- and post are discussed in the next section.

Contrasting the Pre- and Post-test

The differential pattern for the traditional teaching and PBL students also suggested that the various problem sets (pre- and post-tests) could not be pooled together and had to be studied separately. The details of the observed differences are presented below along with possible interpretations and explanations. But, before getting to the distinction between the pre- and post tests (within-subject effects) specifically for each of the two subgroups (i.e., the traditional and PBL students), the overall situation was considered through a doubly multivariate repeated measures analysis. In other words, this analysis tested the main effect of time (repeated measure), main effect of treatment (between effect) as well as their potential interaction (between-within effect) on the four cognitive processes under investigation (dependant variables).

For this specific combined "between-within" analysis, it is important to include only the students who did both the pre- and post-test. There were twelve students who had completed both the pre- and the post-test (see Figure 15).

Figure 16 presents a 3-dimensional overview of the average indices related to the different cognitive processes under investigation (i.e., metacognition, critical thinking, physical intuition, and problem-solving) for these twelve participants as a function of their respective instructional context. Visually, the post-test scores are systematically higher, that is, there is a visible difference between the pre- and post-test for all four processes for both the traditional and the PBL students. This seems particularly important in the case of the problem-solving indices.

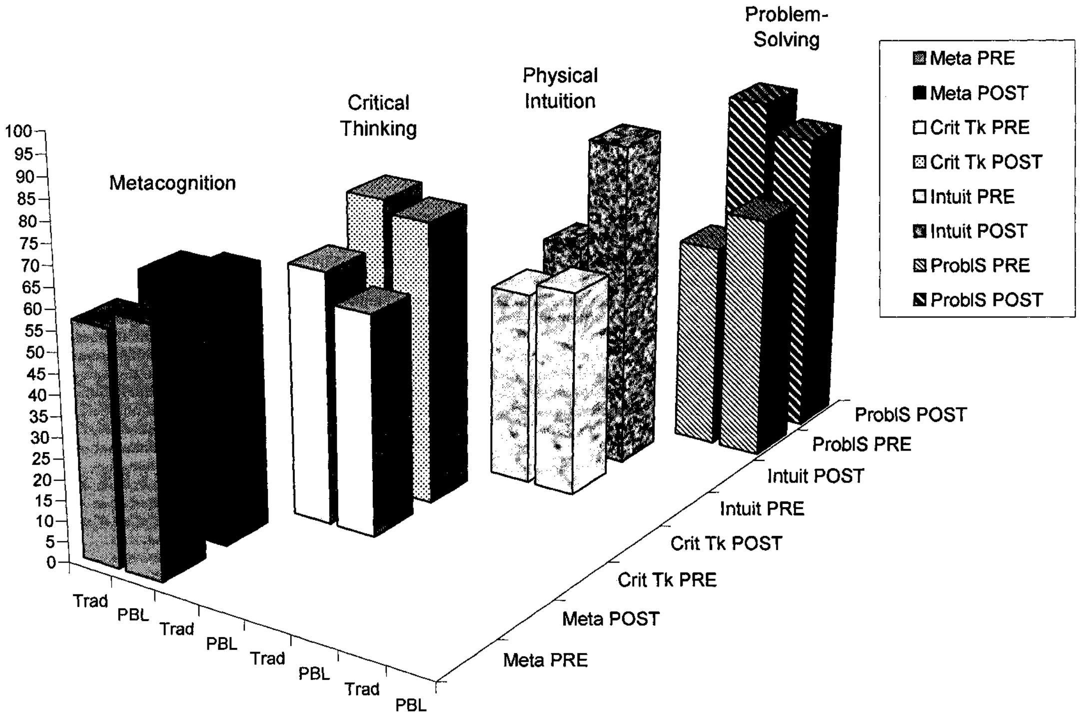

Figure 16. 3-D Comparative Bar Chart of Indices for the Twelve Paticipants who did Both the Pre- and the Post-test

Table 38 presents the means associated with Figure 16.

Table 38
Cognitive Processes Overall Indices

	Pre-test (N=12)		Post-test (N=12)	
Cognitive Process	Traditional Teaching (n=8)	PBL (n=4)	Traditional Teaching (n=8)	PBL (n=4)
Metacognition	56.77	60.42	61.46	63.54
Critical Thinking	61.25	53.75	71.88	68.75
Physical Intuition	46.88	50.00	52.08	79.17
Problem Solving	50.00	59.38	80.48	73.44

In order to determine whether these apparent distinctions were significant or not and to confirm whether it was appropriate or not to pool the traditional teaching and PBL subgroup together, the doubly multivariate repeated measures analysis of variance mentioned above was conducted. These results are presented in Table 39.

Table 39

*Multivariate Tests to Appraise the Effects of Time, Treatment, and Time*Treatment*

Effect	Statistic	Value	F Value	Num DF	Den DF	Pr > F
TREATMENT	Wilks' Lambda	0.37990730	2.86	4	7	.1071
	Pillai's Trace	0.62009270	2.86	4	7	.1071
	Hotelling's Trace	1.63222105	2.86	4	7	.1071
	Roy's Largest Root	1.63222105	2.86	4	7	.1071
TIME	Wilks' Lambda	0.29760478	4.13	4	7	.0497
	Pillai's Trace	0.70239522	4.13	4	7	.0497
	Hotelling's Trace	2.36016103	4.13	4	7	.0497
	Roy's Largest Root	2.36016103	4.13	4	7	.0497
TIME * TREATMENT	Wilks' Lambda	0.44659645	2.17	4	7	.1748
	Pillai's Trace	0.55340355	2.17	4	7	.1748
	Hotelling's Trace	1.23915796	2.17	4	7	.1748
	Roy's Largest Root	1.23915796	2.17	4	7	.1748

The first four rows of Table 39 indicate that there is no significant multivariate effect of treatment at the 0.05 level on the four variables (i.e., metacognition, critical thinking, physical intuition, and problem-solving), pooled over time. All four tests produced the same F values, degrees of freedom, and p-values.

The next rows imply that there is a significant multivariate effect of time on the four variables, pooled over treatments. It might seem unusual to see a main effect of time (p=.0497) because it suggests that *overall*, regardless of the treatment (traditional vs. PBL teaching) or cognitive processes considered (metacognition, critical thinking, physical intuition, and problem-solving), the scores of the pre-test are significantly different from those of the post-test.

When looking at the next rows, the situation gets clearer. The interaction between time (pre- and post-test) and treatment (traditional teaching and PBL) is not significant at the .05 level. This suggests that the differences between the pre- and post-test cannot solely be explained by the inclusion of a treatment such as PBL for some students and that the variations in the cognitive processes score patterns change depending on which treatment group (traditional teaching vs. PBL) one takes into consideration. It is therefore important to look at each cognitive process in the context of each type of teaching.

The associated univariate tests are interesting as well. There is a significant univariate effect (p=.0221) of treatment (pooled over time) on the physical intuition variable as well as a significant univariate effect (p=.0553) of time (pooled over treatment) on the same variable (i.e., physical intuition). These results suggest the need to look specifically at the within-subject effect (pre- vs. post-test) for each treatment (traditional and PBL) and to look for possible differences in terms of the physical intuition scores. Similarly, there is a significant univariate effect (p=.0014) of time (pooled over treatment) on the problem-solving variable. Although there is no univariate effect of the treatment x time interaction for any of the four variables, the largest feature was obtained for problem-solving (p=.1401) which suggests to pay attention to problem solving in the within-subject effects.

Significant differences between the pre- and post-tests did occur in both the traditional teaching and PBL subgroups but these differences were not for the same cognitive processes. It is most interesting to attempt explaining their nature and distinctions. The next sections will systematically address the various simple main effects in this light.

As can be seen in Figure 16, the apparent most important difference from the pre- to the post-test, among the traditional teaching students, appears to be for the "problem-solving abilities" index. For the PBL students, the largest improvement seems to have happened in the "physical intuition" category. Other differences also appear worthy of investigation, so in order to clarify which cognitive abilities and processes had significantly changed for each group, systematic multivariate tests (within-subjects) were conducted.

The only significant difference (at the 0.05 level) from the pre- to the post-test among the four cognitive abilities indices under investigation was "problem-solving", for the traditional teaching students, F(1,25)=22.721, p=0.000. Neither of the other three indices changed significantly from the pre- to the post-test for the traditional teaching students: "metacognition" F(1,25)=0.372, p=0.547; "critical thinking" F(1,25)=0.699, p=0.411 and "physical intuition" F(1,25)=0.030, p=0.863. The tables associated with these analyses of variance are presented in Appendix WW.

For the PBL students, the only cognitive ability index that changed significantly (at the 0.5 level) from the pre- to the post-test was "physical intuition" F(1,12)= 7.416, p=0.018. The other three indices, though displaying raises in their means, did not result in any significant differences: "metacognition" F(1,12)=0.085, p=0.775; "critical thinking" F(1,12)=1.961, p=0.187; "problem solving" F(1,12)=1.724, p=0.214. The tables associated with these analyses of variance are presented in Appendix XX.

The distribution of the scores for each cognitive process (metacognition, critical thinking, physical intuition, and problem-solving) and time (pre- and post-test) are panelled by treatment (traditional teaching vs. PBL) into pyramid graphs (see Appendix YY) to provide a more visual representation of the various index scores just discussed.

Summary of the Cognitive Abilities when Solving Problems

Two of the three *a priori* hypotheses were verified. First, no significant difference was observed between the traditional teaching students and the PBL (to be) students in the pre-test. In other words, students who ended up in the PBL group did not display any superior or distinct cognitive ability or problem-solving capacity in their pre-test problem solutions and plans. It is reasonable to conclude that, besides maybe an interest or a motivation to experience a different approach to problem-solving via involvement in the PBL activities, they were otherwise representative of their peers from the same cohort.

Given the stability of the traditional teaching context for the traditional teaching students, no significant differences between the pre- and post-test was expected for the traditional teaching students but this did not turn out in the expected way. A significant improvement in the problem-solving index was observed. The score of the other three cognitive processes under investigation also increased though not significantly for these traditionally taught students. Various explanations can be considered to justify why the problem-solving index became significantly bigger. One could postulate that, despite the professor's approval of the problems of the post-test and his appraisal that they were similar in difficulty to those of the pre-test, maybe the problems of the post-test were easier than those of the pre-test. However, it could also be argued that if this had been the case, then a similar result should also have been observed among the PBL students. Given the equivalence of the two subgroups in the pre-test, if any differences at all were to be observed from the pre- to the post-test, all participants should have experienced similar and comparable changes. But, no significant improvement in the problem-solving index was observed for the PBL students.

In attempting to understand the reasons for this change in the problem-solving index for the traditional students, it is useful to recall the four specific indicators that were considered in composing the problem-solving index: a) the ability to recognize and acknowledge assumptions, b) the ability to translate or represent the problem into a graphical form, a sketch, or pictorial representation, c) the ability to translate written statements into mathematical and physical representations, and d) the overall completeness and accuracy of the solution. All four indicators, interestingly enough, were not explicitly asked for in the problem statements, but these are observed as known features naturally occurring in good problem-solvers. It is reasonable to think that an increased familiarity with the process "imposed" on the participants in the problem sets had an influence on these indicators. After all, twelve of the fourteen participants in the post-test had also completed the pre-test and therefore had already experienced the unusual context of these problem-solving exercises.

Breaking down one's problem-solving strategy into small units and steps, and most of all, expressing them with words and sentences was not a familiar activity for any of the students. Physics students in general are seldom required to justify their approach to problems: they simply solve them without detailed explanations. With these problem sets, the students were prompted to provide as much written detail as possible in their plan, justifications, and revisions. The generally longer and elaborate developments observed in the post-test, including more articulate assumptions, and the apparent increase in the intention to convey or share a clear meaning using both the language of physics (graphs and equations) and the English language in developing the overall solution, seems to support this "familiarity with the process" argument being displayed in the post-test. Informal discussions with traditional students either immediately or a few days after the post-test also suggested an increased comfort with the overall procedure asked of them (e.g., "… this time I was much better at explaining what I was thinking. I think you'll like what I have written this time (grin)…", "… I wrote loads of pages today, I could not believe it myself, and I did all kinds of sketches too…", "… I knew you were going to ask us to write a lot of stuff this time. The first time I kind of panicked you know, but not today …"). Most of them knew exactly what to expect when they accepted to complete the post-test.

In other words, it seems that a kind of maturation or carry-over effect resulting from the exposition to the pre-test took place in the post-test. In general, carry-over effects are not desirable in a repeated measures design. But, in this case, if the task requirements of the pre-test can be considered a form of instruction, it probably helped the traditional students to perform better in the problem-solving indicators and this resulted in experience and increased comfort with the overall procedure.

The PBL activities were expected to help the PBL participants gain a superior awareness of their own cognitive processes and/or gain confidence in their ability to deal with unfamiliar problems. A resulting improvement (significant or not) was expected in the scores linked to metacognition and/or physical intuition among the PBL students. A significant increase in the physical intuition index (i.e., indicators which pertained to the second and purposefully unfamiliar problem) was actually observed among the PBL students in their post-test. It can be hypothesized that, despite its short period of duration, the PBL activities did somehow trigger or stimulate the physical intuition indicators of the PBL students: a) the ability to anticipate trends or alternatives, b) the ability to clearly identify gap(s) in knowledge or missing info in the problem, and c) the ability to generate analogies. Presumably, the PBL experiment fostered the students' ability to identify what they know and what they don't know, see similarities with prior experiences and knowledge, and find the courage to venture into imagining how they could tackle a complex problem.

The PBL intervention possibly contributed to the reduction of the students' anxiety in the face of an unfamiliar task, now seen more as a challenge rather than a threat. After practicing in a supportive and safe environment to approach an unfamiliar problem, the PBL students possibly felt more self-confident when dealing with another unfamiliar problem (this time in the post-test). It is to be noted that, unlike the PBL students, the traditional format students did not display any significant improvement of their physical intuition index in the post-test.

Some of the written comments by a PBL student illustrate this new taste for challenge: "I know I could deal with this if I had all my books and a bit more time…". It was actually observed by the researcher that the four PBL students systematically scanned their class notes and textbooks during the post-test in search for the best use possible of the resources they had access to while only three traditional students of the remaining ten participants to the post-test thought of doing so. As was the case for the pre-test, the researcher had clearly indicated to the participants that they could use a calculator as well as any class notes or textbook they had. In addition, in case someone had forgotten their textbook, the researcher had brought additional copies of the assigned textbook for the electromagnetic waves course and calculators with her and made them available to the students during the post-test. Nonetheless, referring to the resource material remained limited.

There is no doubt that many of the traditional format students could have gone a lot further in the second problem of the post-test, despite its difficulty, had they at least considered trying to research the useful resources within access, including a complete section on lossy transmission lines in their textbook that gave a number of hints as well as definitions of most parameters and measure units, yet without providing all the necessary information. This problem was meant to be challenging. Nonetheless, there were accessible resources as well as parallels that could have been drawn with more familiar problems using already known variables of their introductory course of electricity and magnetism. It appeared that the complexity of the second problem overwhelmed these students. The following excerpts are illustrations of such feelings of helplessness in three traditional format students dealing with the second-problem of the post-test.

For instance, a student wrote: "I don't know what a lossy transmission line is. I don't know what G stands for. I'm not even sure if I interpreted L, R, & C correctly" (see Appendix ZZ for the original excerpt). Another student wrote: I don't feel like I really know what inductance means. My sense of it is pretty vague. I use it in problems, but when it comes to figuring it out 'from scratch', I don't know what to do" (see Appendix AAA for the original excerpt). The third excerpt (see Appendix BBB for the original excerpt) especially seems to express an overall discomfort that goes much beyond the problem at hand and applies to the entire course. A student wrote:

> I don't know how to answer this. I often feel like I understand how to solve specific problems, but when I am given a dissimilar problem on an exam, I am lost. I feel like there is too much theory in electromagnetism class and not enough practical application. In my current class, I struggle with problems that are way too hard on home works and thus don't understand how I can otherwise apply the theory I learn. I feel like I was lost in a jump between the difficulty of the material that I learned in high school and the material I am learning now.

An excerpt from one of the PBL students (see Appendix CCC for the original excerpt), gives an illustration of a totally different level of confidence and self-efficacy in approaching the very same problem (e.g., “First thing that comes to mind…”, “Inspecting my notes, I found two relationships…”, “This [is] important because it shows how to…”).

Overall, to be exposed to the process of planning and detailing one’s plan of action and solution to a problem seems to facilitate the development of stronger problem-solving strategies, as observed with traditional teaching students. The other three indices (metacognition, critical thinking, and physical intuition) also increased but not significantly.

It is not possible to say with any degree of certainty whether or not the PBL students also benefited similarly from the mere exposition to the pre-test. Though their problem-solving index for the post-test was higher than for the pre-test, the increase was not statistically significant and this pattern was similar in their metacognition and critical thinking indices. It can be hypothesised that the important increase of the physical intuition index, and related indicators, among the PBL students somehow eclipsed their other indices. Since all the indicators of the physical intuition pertained to the second and unfamiliar problem, it seems plausible to associate this significant improvement, which was observed only among the PBL students, with the consequences of the PBL activities these participants were involved in.

The PBL problem that served as the starting point to the PBL sessions clearly was a complex and unfamiliar problem, drawing from a number of already mastered concepts but also involving a number of concepts not yet addressed in class along with some completely novel features. Presumably, the participants of the PBL activities derived a stronger confidence in their ability to deal with difficult problems along with inquisitive strategies to gather information on an unfamiliar topic.

Learning to Solve Problems in a PBL Environment

To answer the fourth research question concerning the cognitive actions, processes, and activities that students engage in while learning to solve problems in a PBL environment, the verbatim transcription of the video recordings of the tutored PBL sessions constituted the main data source. The written output of the PBL students' work and progress as a group, which they recorded themselves on flip-chart sheets, had been integrated within the verbatim transcript as it constituted a tangible product of the PBL sessions and team meeting. Appendix DDD presents a collection of reduced and scanned flip-chart sheets produced by the PBL students.

What is going to be addressed in this section pertains to the interactions between the students and the tutor and among the students themselves during the two tutored sessions. The nature of the tutor interventions and supervision are of particular interest in the context of this study, just as the nature of the instructional interventions of the traditional teaching professor were central to the Electromagnetic Waves lectures that were observed.

Descriptive Features of the PBL Sessions

Before describing the results of the log-linear analyses per se, some frequency counts are presented as they allow for a description of the PBL sessions, including the nature and frequency of the interventions of the different actors in each of the two tutored PBL sessions. These highlight how the tutor adapted to the students' needs as a function of their progres and how the students also called on different cognitive actions depending on the context. The tutoring and students involvement are addressed in the subsequent sections.

Tutoring

The tutor used a variety of tutoring strategies for both of the PBL sessions. But, as can be seen in Table 40, he did not use the same strategies with the same frequency during both sessions. The descriptions of the various tutoring strategies appear in the Codebook (see Appendix OO). An excerpt of the tutor interaction with students during Session 1 is also presented in Appendix EEE along with the corresponding coding of the tutoring strategies.

Table 40

Tutoring Strategies During PBL Sessions 1 and 2

Tutoring Strategy	Number of Units of Coding		
	PBL Session 1	PBL Session 2	Total Both Sessions
(4 1 1) /QUESTION	37	13	50
(4 1 2) /INSTRUCTIONS	17	3	20
(4 1 3) /HINT	16	5	21
(4 1 4) /EXPLAIN	4	9	13
(4 1 5) /TELL	10	2	12
(4 1 6) /DEMO	22	1	23
(4 1 7) /CHECK	8	2	10
(4 1 8) /EVALUATE	16	54	70
(4 1 9) /REQUEST	20	8	28
(4 1 10) /Q&A (self)	2	0	2
(4 1 11) /RESPOND	0	2	2
(4 1 12) /ADVANCED ORGANIZER	0	0	0
(4 1 13) /CLARIFY	1	9	10
(4 1 14) /REPEAT or ELABORATE	2	1	3
Total	155	109	264

As can be seen from Table 40, the tutor provided more guidance in the form of questions, hints, instructions and demonstrations during the first session than in the second one. He also checked the students' understanding and prompted them ("Request" strategy) to apply specific procedures more often. In the second session, however, the students had already developed a much more autonomous, self-confident, and fluid functioning. They needed a few clarifications once in awhile to go on but, generally speaking, the tutor intervened less often than in the first PBL session.

What the students needed most in the second sessions was just-in-time assessment of their progress and outcomes. The results indicate that the tutor did provide more evaluations of their reasoning, results, and products during the second session. The results of a log-linear analysis, presented in a forthcoming section, confirm that the two PBL sessions were actually significantly different in terms of the use of tutoring strategies which tends to confirm that the tutor intentionally adjusted to the students' needs in the choice of his interventions and interactions with them.

Student Involvement

The nature of the student involvement is made apparent through the examination of the counts for the different types of activities in Table 41. The three types of activities that emerged from the analysis of the data are a) "Solving Problem" (i.e., actually applying procedures or reasoning to solve the problem, performing the appropriate calculations or manipulating equations or expressions, obtaining a solution, etc., b) "Working on Learning Issues" (i.e., reading materials to learn, clarifying and sharing findings with others, discussing conceptual understanding to come up with a common knowledge basis and understanding of things, etc.), and c) PBL Tasks and Assignments (i.e., discussions about the procedure of working as a team or working in a PBL format, organizing work, assigning themselves specific tasks and responsibilities, etc.).

It can be seen in Table 41 that virtually all of the problem-solving happened during the second session. Working on learning issues is prevalent in both sessions which suggests that it constituted a major aspect and characteristic feature of PBL. Considerable time was spent on identifying gaps in knowledge and relevant concepts, collecting new as well as confirmatory information, clarifying knowledge and discussing it in the group before attempting to apply it in an effort to solve the problem. The slightly smaller number of coded units dedicated to the discussion of the "PBL Tasks and Assignments" in the second session seems to indicate that the students were becoming more comfortable with the overall PBL process and therefore needed to spend less time on organizing their work or debating who would be responsible for what.

Table 41
Type of Activities by Session and Speaker

Type of Activity	Session 1					Session 2					Total Sessions 1 & 2
	Stud 1	Stud 2	Stud 3	Stud 4	Total Session 1	Stud 1	Stud 2	Stud 3	Stud 4	Total Session 2	
Solving Problem	2	0	0	0	2	102	64	59	37	262	264
Working on Learning Issues	53	90	91	61	295	98	62	55	24	239	534
PBL Tasks or Assignments	27	30	24	18	99	19	48	16	5	88	187
Total	82	120	115	79	396	219	174	130	66	589	985

Table 41 also shows the relative involvement of the different students in the various types of activity and also whether their level of involvement changed from one session to the other. Student-1, for instance, was the most vocal of the four but he appears to have been much more vocal in the second session than in the first. Student-4 was the least vocal of the group. Student-3's involvement remained about the same while Student-2 was more present in the second session. Student-2's voluntary monologue, when summarizing the groups' state of advancement at the beginning of the second session, has to be taken into account from that perspective.

As a complement, the following pie chart (Figure 17) summarizes the involvement of the various participants for both sessions combined. The unit of conversation was a paragraph. Overall, the tutor spoke less often than most students (i.e., three out of four). It can be noted that all of the coded units, using all coding trees, are represented on this graphic.

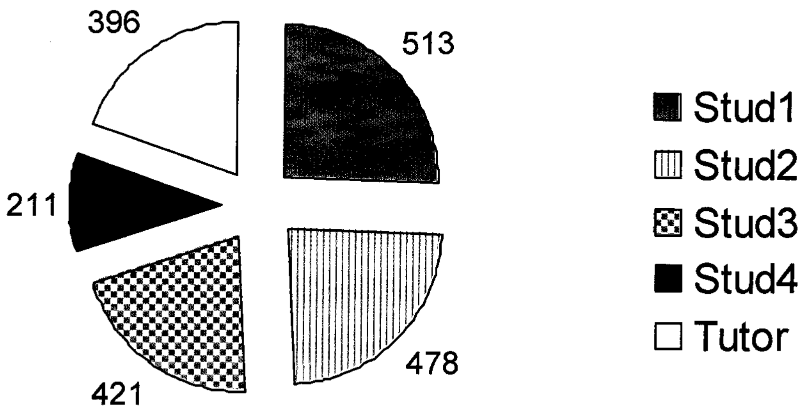

Figure 17. Repartition of the Coding Units by Participant

Table 42 sheds a different light on the students' apparent specialization in the specific aspects of the problem frame and to the dimensions to which they made the greatest contribution. The problem frame can conceptually be divided in two sub-problems: the waveguide problem and the shielding problem.

The summary made by Student-2 is very visible this time from his contribution to the "Modes in Waveguides", "Choose a dielectric" and "Write the Cut-off Frequency Equation" categories. These correspond to the final stages of the waveguide sub-problem that had been completed during the student meeting. At the beginning of the second tutored session, Student-2 presented orally the group's thinking and various attempts which led to successfully solving this portion of the overall problem related to waveguides.

Student-2 and Student-3 had been particularly active in their attempt to document the shielding problem during the first session. No conclusion or solution was achieved though and, during the second PBL session, some assistance was provided to the group in the form of a text on how to calculate shielding. During the second session, it was Student-1 and Student-2 who were the most productive in dealing with the documentation and understanding of the theoretical aspects of shielding. Student-1, Student-2, and

Student-3, however, contributed almost equally to the concrete application of this knowledge and to the final solution and calculations related to the shielding problem. Student-3's contribution in figuring out logarithmic scales and decibels proved particularly determinant for the success of the group on that specific sub-problem.

Table 42 then illustrates who contributed to what portion of the problem resolution as a function of the tutored session (first or second). It can also be noted that the identification of properties (whether they were related to microwaves in general or to shielding) occupied an important proportion of the students' time. This is aligned with similar conclusions on "Working on learning issues" already highlighted in Table 41.

Table 42
Problem Frame by Session by Speaker

Problem Frame	Node Set	Session 1					Session 2					Total Sessions 1 & 2
		Stud 1	Stud 2	Stud 3	Stud 4	Total Session 1	Stud 1	Stud 2	Stud 3	Stud 4	Total Session 2	
Waveguide Problem	ID of Microwave Properties	31	35	39	27	132	5	2	0	0	7	**139**
	Modes in Wavegudes	1	1	4	1	7	3	8	0	0	11	**18**
	Choose a Dielectric	0	3	3	0	6	5	18	2	1	26	**32**
	Write Cut-off Freq Equation	0	0	0	0	0	0	15	0	0	15	**15**
Shielding Problem	ID of Shielding Elements and Properties	6	28	23	13	70	14	14	3	4	35	**105**
	Determine Size of Hole	0	0	0	0	0	29	30	25	15	99	**99**
Total		38	67	69	41	215	56	87	30	20	193	408

There is another aspect of the apparent specialization of the students, within their team, that can be illustrated through the examination of the cognitive actions they engaged in as a function of the session. The descriptions of the cognitive actions were presented in the Codebook (see Appendix OO).

Table 43 illustrates how often the four participants engaged in various cognitive actions.

Table 43
Cognitive Actions by Session by Speaker

Cognitive Actions	Session 1					Session 2					Total Ses-sions 1 & 2
	Stud 1	Stud 2	Stud 3	Stud 4	Total Ses-sion 1	Stud 1	Stud 2	Stud 3	Stud 4	Total Ses-sion 2	
Interpret State	9	10	14	8	41	0	1	0	0	1	42
Plan Action	5	1	3	2	11	2	2	3	1	8	19
Plan Goal	13	7	14	8	42	2	1	0	0	3	45
Test Conditions	0	0	0	0	0	30	32	14	7	83	83
Execute Action	7	2	3	0	12	2	0	2	1	5	17
Evaluate	0	0	0	0	0	34	19	22	19	94	94
Explain Theory	3	4	1	3	11	20	21	13	2	56	67
Explain Results	0	0	0	0	0	7	19	6	3	35	35
Explain Procedure	0	0	0	1	1	4	1	7	0	12	13
Correct	2	0	3	3	8	8	4	1	1	14	22
Reason	40	80	71	49	240	104	73	64	32	273	513
Total	79	104	109	74	366	213	173	132	66	584	

When looking at Table 43 globally, it is not surprising to notice that the "interpretation of the state of the problem" and "planning (goals and actions)" were more often used during the first session than in the second. They constituted a preparation or warm-up activities. On the other hand, actions such as "testing the conditions for the application of a procedure" as well as "evaluating" or "explaining results" and "explaining a procedure" were almost absent from the first session while they were more prominent during the second PBL session. These appeared to occur only when the students had already resolved most learning issues and achieved at least some preliminary results. They did not take place during the initial attempts to capture the essence of the task at hand.

"Reasoning" was however consistently used in both sessions and also constituted the dominant cognitive action for all participants, regardless of the session. The other two cognitive actions that were involved most frequently were "testing conditions for the application of a procedure" and "evaluating results". This is a very interesting finding given that both actions require strong metacognitive abilities. The very context of learning in a PBL setting seemed to have led the participants to resort to their metacognitive skills as they found their way to a robust and successful problem solution. Moreover, it is particularly encouraging to see that these two specific cognitive actions were performed by all of the four participants at comparable rates.

However, when looking more specifically at the individual contribution of each participant, the "specialization" aspect already observed emerges again. The participants did not always engage in the same cognitive actions equally. Each person seemed to excel in one or a few which in turn provided a rich blend of capacities when considering the team as a whole.

For instance, when it came time to plan the team's goals, Student-1 and Student-3 were the most active and productive ones. Student-1 demonstrated initiative in executing actions as well as clear thinking when reasoning. Student-2 also contributed significantly to the reasoning of the group with his facility for thinking aloud. Particularly in the first session, Student-4 identified mistakes and reformulated when necessary. During the second session, Student-1 and Student-2 were articulate when sharing findings and explaining theoretical concepts for the benefit of the group. Student-2 was efficient and vocal in explaining the team's results to everyone while Student-3 was most comfortable with the explanation of procedures. Overall, Student-1 was the most vocal. However, during session 1, Student-2 and Student-3 took the lead. Student-4 remained less vocal but his interventions were generally to the point and contributed toward keeping the team on track.

In addition to complementing the description of the PBL sessions, the coding counts and cross-tabulated data extracted form the transcripts with N-Vivo also allowed for log-linear analyses, which are presented in the next section.

Log-linear Analyses and Interpretations

The log-linear analyses allowed for the testing of possible interactions between variables. Their strength resides primarily in the possibility to analyse multi-way contingency tables. In the following sections, the results pertaining to one 2x13 table related to tutoring, one 2x4x3 table related to the type of activities, and one 2x4x11 table are discussed.

Tutoring

The data used for the log-linear analysis of the session by tutoring contingency table were obtained from Table 40 presented earlier. Only the row pertaining to the advanced organizer strategy was omitted because this strategy was not utilized by the tutor in either of the two sessions. Table 44 summarises the findings.

Table 44

Maximum Likelihood Analysis of Variance Using a Saturated Log-linear Model of the Tutoring Data

Source	DF	Chi-Square	Pr > ChiSq
session	1	4.35	0.0371
tutor	12	104.48	<.0001
session	10*	65.32	<.0001
Likelihood Ratio	0	.	.

NOTE: Effects marked with '*' contain one or more redundant or restricted parameters.

Considering the maximum likelihood analysis of variance given by PROC CATMOD for the saturated model, the possible interaction term is significantly different from zero at the 0.05 level. There is a confirmed interaction between the session and the tutoring strategy. This suggests that the tutor used different tutoring strategies as a function of the session that the students were engaged in and presumably adapted intentionally to their specific needs for support, clarification, explanation, evaluation, etc.

The students also displayed a differential pattern of the type of activities or of the cognitive actions they involved as a function of the session. The corresponding log-linear analyses are presented below.

Session, Speaker, and Type of Activity Interaction

A saturated model was used to allow for all the possible interactions. As can be from Table 45, all main effects and all interactions are significant at the 0.05 level.

Table 45
Maximum Likelihood Analysis of Variance Using a Saturated Log-linear Model of the Type of Activity Data

Source	DF	Chi-Square	Pr > ChiSq
speaker	3	38.96	<.0001
activity	2	158.05	<.0001
speaker*activity	6	19.34	0.0036
session	1	12.77	0.0004
speaker*session	3	33.59	<.0001
activity*session	2	23.96	<.0001
Likelihood Ratio	3	17.33	0.0006

Considering the maximum likelihood analysis of variance given by PROC CATMOD for the saturated model, all main effects and all of the possible interaction terms are significantly different from zero at the 0.05 level. Thus, there is an interaction between the three possible pairs of variables which implies a three-factor interaction in the data. It can be concluded that the association between the speaker and the type of activity depends on which PBL session is investigated.

Overall, this suggests that the students did not engage in the same activities in sessions 1 and 2 and that the role of the students also changed (i.e., the most vocal people in session 1 were not the ones contributing the most in session 2 and vice versa). As it was visible in the descriptive tables already presented, some students were contributing more in documenting the learning issues while others actively applied the concepts and derived actual answers. This situation appears reasonable given the internal functioning of a PBL team where each person is responsible and accountable for documenting and informing the others on specific aspects of the problem.

At the end of the first tutored session, as well as at the end of the student team meeting, each of the four participants left with a clear mandate to occupy themselves during their self-directed study. When combined with each student's individual strengths and learning style, it was to be expected that a "specialization" in the roles and contributions was going to appear along the way.

Session, Speaker, and Cognitive Actions Interaction

An analysis similar to the previous one, also a saturated model, was conducted to test the apparent interaction between the session, speaker, and cognitive actions variables. Similar conclusions were derived. Table 46 below summarizes the corresponding results.

Table 46
Maximum Likelihood Analysis of Variance Using a Saturated Log-linear Model of the Cognitive Actions Data

Source	DF	Chi-Square	Pr > ChiSq
speaker	3	12.63	0.0055
cogn	10	763.66	<.0001
speaker*cogn	30	47.43	0.0226
session	1	0.01	0.9236
speaker*session	3	30.05	<.0001
cogn*session	6*	46.22	<.0001
Likelihood Ratio	10	13.46	0.1991

NOTE: Effects marked with '*' contain one or more redundant or restricted parameters.

Here, the main effect of session alone is not significant but the three possible interactions are all significant at the 0.05 level. Consequently, the interaction between the cognitive action and the speaker variables vary with the session under investigation. Different students engaged in different cognitive actions depending on the session. The patterns among the PBL participants varied, as it had already been anticipated from the descriptive review of the cognitive actions among the participants.

Summary on Learning to Solve Problems in a PBL Environment

As the students became more familiar with the PBL process, they spent less and less time discussing procedural features and concentrated on identifying and documenting all of their learning issues. Even in the face of a challenging problem, the different strengths and perspectives brought in by the different members of the team helped identify, in an exhaustive and effective way, most of the learning issues at the very beginning of the process. The students learning physics in a PBL context did not seem to engage blindly in the problem-solving phase and appeared to resist the temptation to promptly crunch numbers inserted in a seemingly appropriate equation.

The teamwork likely had a role to play in this situation. In other words, the personal approach of each student (e.g., theoretical, applied, intuitive, or meticulous, etc.) probably tended to smooth out any more drastic tendency that one individual might otherwise have had. The thinking aloud mode of functioning, which proved an effective method for in-time and continuous updates, likely helped the students postpone the more applied (or concrete) steps of the problem-solving until a conceptual and mutual understanding had been reached. This care in dealing with the learning issues first appears to be a promising asset to foster deep learning for PBL participants.

Cognitive actions, such as testing conditions and evaluating results, with a clear relationship to metacognition also appeared to be stimulated for all of the participants. Once the task was clear and the concepts understood, the solution and related computations were performed and verified promptly. The students' individual strengths and natural pre-dispositions, either to use specific cognitive actions or to deal with particular content, complemented one another and the group as a result became more complete and effective on every aspect of the task.

Given the limited level of support provided by the tutor in a nonetheless challenging problem-solving setting, the PBL students accomplished a considerable amount, including a successful completion of the problem at hand within only two tutored sessions and one team meeting. All of this took place without any prior experience of PBL by the participants. The tutor, in an authentic PBL perspective, intervened as little as possible and only when the students seemed to need support or had reached a dead end. He was able to resist being a handy information provider.

The PBL participants also demonstrated excellent abilities in identifying their needs and in managing resources. Sharing the results of their self-directed study helped the group and allowed the strengths of each member to shine at different points in time during the process. All of the four students brought a unique contribution to the team effort. It is unlikely that any of them individually and functioning alone, would have achieved similar results within such a short period of time.

CHAPTER 5 – GENERAL DISCUSSION AND IMPLICATIONS

In this fifth and last chapter, the findings and their implications will be reviewed and put into perspective in the light of the current literature on similar features. This will be followed by the original contributions of the study. Then, the limitations of the study will be acknowledged. Finally, recommendations to inform future research and instructional practices in physics education will be made.

Review of Findings

The participants in this study were advanced undergraduate physics students enrolled in an electromagnetism course. In the first phase of the study, the students' approaches to learning and perceptions about their role as physics students were examined via a survey developed especially for that purpose. This data helped answer the first research question. It appears that most participants are highly motivated and dedicated students who set high standards for themselves, work hard, and are generally self-disciplined. Given the demanding program they are enrolled in combined with their overall expressed comfort in their physics program, such commitment was, to some extent, to be expected, but this is nonetheless very positive.

Just as desirable for physics learning are the students' approaches that depict intentional and strategic approaches to prepare for examinations, including trying to anticipate what the assessment could address as well as dealing with the course material on a daily basis. These characteristics are particularly promising because of the direct metacognitive connotation they imply. Students expect to put a lot of effort into their course work in order to get the best out of their learning experience. From the same perspective, most students prefer being challenged rather than dealing with easy content, in order to stimulate their learning. The "Physics is within my reach" attitude which prevails among the participants is a similarly positive asset.

Not surprisingly, grades are considered very important to the students and rote memorization remains a limited yet ever popular strategy among physics students. The roles the students cast themselves into are typically passive, mostly restricted to taking notes, and further characterized by a low, in-class participation (i.e., few questions, minimal interactions with the professor, virtually no exchange between students). Whether this situation is actually what students really believe their role to be in physics as a result of their prior experience in their program or whether it depicts a tendency to avoid asking questions in front of the group remains unresolved. In either case, such a limited perception of their role as physics students raises questions. One can ask whether this has anything to do with perceived or real messages received directly or indirectly from the professor and whether or not opportunities are actually created for the students to assume a more active role in class.

The second research question addressed the characteristics of electromagnetism instruction in the traditional format and using a PBL format. It was observed that the lectures, although very traditional in nature and minimally interactive, included an important number of the established characteristics of effective lectures (e.g., a good organization and articulation of the content, clarity of expression, mastery of the subject matter, use of analogies and examples, modelling of problem-solving, linking concepts together within course and across curriculum, etc.).

In fact, these lectures were led by an experienced lecturer who, although he had not been formally trained in pedagogy, was able to intentionally foster the development of his students' cognitive competences. Problem-solving and critical thinking were often modelled out loud by this professor in worked examples and demonstrations. Some metacognitive elements, such as monitoring during particularly long derivations or demonstrations were also modelled to some extent. There is no clear evidence, however, that physical intuition was modelled for the students. The high level of preparedness of this professor for each class and his ease in answering the students' questions never placed him in an unexpected or unfamiliar situation that would have necessitated invoking physical intuition. Considering the observed characteristics and the excellent quality of the modelling offered in these lectures, they cannot be considered representative of lectures in general. Even without the active participation of the students, these lectures offered a rich and consistent learning experience for the students.

The PBL instructional context depicted a completely different situation. The students were the main actors in this context and this meant that they were active constantly. They were responsible for identifying and documenting what information they needed to know in order to carry on. With occasional yet carefully chosen questions and hints, the tutor intentionally modelled the four cognitive processes under investigation. The tutor never imposed his views but his suggestions made the students think about or reconsider their perspectives and strategies. The tutor's interventions sometimes related to the PBL process and aimed at guiding the students in a context they were not familiar with. He also provided validation through formative evaluation.

Overall, both instructors offered a competent performance in their respective instructional context. They also appeared to share many views about teaching and learning. For instance, the desired outcomes and cognitive abilities to develop among students identified by these two instructors are very similar. The importance of problem-solving competence, critical thinking and self-directedness are also similar. The main difference between the two resides in the definition of the professor's responsibility in organizing and transforming knowledge. The traditional professor sees himself as solely responsible for an expert dissemination of the content, drawing on his experience and subject knowledge. The PBL tutor perceives himself as a facilitator, accompanying fully accountable students in their quest for knowledge and understanding.

With the third research question, the presence of the indicators of metacognition, critical thinking, physical intuition, and problem-solving in the solutions to problem sets was verified. For the traditional students, the unexpected significant increase in their problem-solving indicators from the pre- to the post-test is hypothesized to be related to the exposure to the pre-test itself. Among the PBL students, the significant rise of the physical intuition indicators appears to be the positive consequence of the PBL intervention. It is likely that the non threatening environment of the PBL helps develop comfort in dealing will ill-defined and unfamiliar problems.

The fourth research question addressed the cognitive activities and actions that students engaged in when learning to solve problems in a PBL environment. The teaching strategies of the tutor to facilitate the PBL process were also investigated. It appears that, among the three main types of cognitive activities that the students engaged in during PBL (i.e., solving problem, working on learning issues, and PBL tasks or assignments), those related to working on the learning issues are the most prevalent and determining for the final outcome. When looking at cognitive actions, reasoning was used consistently in both PBL sessions. Planning goals and interpreting the state of the problem were prevalent during the initial tutored session while testing conditions and evaluating progress and results defined the second one.

An interesting tangential finding was that, despite the novelty of the PBL process for the four participants, they seemed to rapidly learn to function effectively in this new environment and use their individual strengths in a complementary fashion toward achieving a common goal.

Implications of Findings

The results of this study have direct and indirect implications for physics students and instructors. Some implications bring a reassuring perspective on the current situation of physics education while others pertain to challenges that need to be addressed. The nature of these implications suggests that they can be organized around three main themes: a) students' perceptions, b) students' cognitive processes, and c) instructional contexts. For each theme, a number of specific implications are discussed.

Students' Perceptions

Students' perceptions correspond to the subjective and personal perspectives they have of their physics courses and learning experience. Perceptions can be more or less accurate but they are always significant and real for the person entertaining them.

Students' Role in the Classroom

The apparent comfort of students when posing questions to the professor immediately before class suggests that they are more active and comfortable in small groups. This is consistent with the findings of Guay and Vallerand (1997), who found that competition in academic contexts tended to reduce intrinsic motivation and achievement, while collaboration generally had positive consequences on these variables. This study highlights the need to consider ways in which physics courses could be made more interactive and, more importantly, that increased levels of interaction in the classroom would not introduce a new level of discomfort for participants. In their study on professors' strategies to encourage students to formulate insightful questions about science and express their own ideas during in-class discussions, van Zee, Iwasyk, Kurose, Simpson, and Wild (2001) concluded that students' questions occurred when the professors could set up a classroom context that: (a) explicitly elicited questions from students, (b) engaged students in conversations about familiar contexts in which they had made many observations over a long period of time, (c) created comfortable discourse environments in which students could try to understand one another's thinking, and (d) established small groups where students were collaborating with one another.

Considering that active learners can be empowered by an active involvement and inquiring approach to learning (Linn, 1990), the low level of class participation and the small number of questions typically asked by the students in this study raised a number of questions. For instance, to what extent is the instructional context conducive to active student participation? To create such an environment, it takes more than openness on the part of the instructor to entertain questions. Learning activities must be designed and implemented during class time to not only engage students in active learning but to lead them more directly toward intended learning outcomes (Saroyan & Amundsen, 2004).

Physics is a very competitive domain for students where making a mistake might be perceived as a weakness as opposed to a learning opportunity for everyone present. The perceptions of the students about what the professor and/or other students might think if they ask a "not-so-good" question has to be taken into account if the intent is to foster active participation.

"Physics is Within my Reach"

It is particularly encouraging to see a "physics is within my reach" overall attitude among students. Considering that this study involved advanced students, it might be argued that such a perception was to be expected. However, the average time for withdrawal and retention rates at the specific institution where this study was conducted indicate that masters students in the physical and applied sciences drop out less in early years and more in later years than their counterpart in other large Canadian universities[15]. This tendency was also observed in most disciplines at both the masters and doctoral in this institution. Consequently, it should not be assumed that advanced students, even at the undergraduate level, are automatically less at risk for withdrawing. A positive attitude toward their discipline combined with a high level of comfort in their program, therefore, is a promising feature of the students who participated in this study.

This "Physics is within my reach" perception could be promoted in the population in general to encourage more students, including females, to consider studies and careers in physics in particular and in science, in general. "Fostering positive attitudes and epistemologies is in itself an important instructional outcome [in physics] that could serve the students well beyond the course in question" (Lising & Elby, p.372). The idea of making physics popular has been an ongoing challenge for decades (Goodstein, 1990).

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[15] The Principals of ten large Canadian universities commissioned a comprehensive retention study which was completed in 2002. Aggregated data from this study is reported on by Berkowitz (2003).

Science instruction often appeals to only a small segment of the population (Linn, 1990). Too often perceived as a dry and unapproachable discipline reserved especially for smart people, physics now seems to increasingly be the focus of a number of endeavours and programs to make it popular and to attract future students (Simmons, 2005). An example of these initiatives is "The World Year of Physics 2005", which is a United Nations endorsed international celebration. It aims specifically to raise worldwide awareness of physics and physical science through a series of coordinated events and publicity efforts.

Self-efficacy

In the present study, a number of students explained their inability to deal with some of the unfamiliar problems, in either the pre- or post-test, due to a lack of knowledge about the concepts. Some students explicitly referred to this feeling of helplessness by simply saying that they had "no idea" whatsoever about what to do. In contrast, there were other students, with similar prior knowledge who were equally unprepared to successfully solve these challenging problems but, nonetheless, generated a few hypotheses or attempted to design a possible plan of action based on what they already knew and understood. A question that begs asking is why were some students paralysed and others stimulated by challenging problems? Pajares' (1996) findings shed some light on this question. "[A]cademic performances are in large part the result of what students actually come to believe that they *have* accomplished and what they *can* accomplish. This helps explain why students' academic performances may differ markedly when they have similar ability" (p. 1).

The positive attitude of the PBL students, in particular in the face of a challenging task, highlights the potential of using unfamiliar problems as a means to trigger students' cognitive processes and problem-solving abilities. This converges with Bandura's conclusions: the self-evaluation process essential to the determination of people's efficacy can be developed better in the face of challenging activities than in the context of tasks that are perceived as easy (Bandura, 1986). "People with high assurance in their capabilities approach difficult tasks as challenges to be mastered rather than threats to be avoided" (Bandura, 1994, p. 71). The perceived self-efficacy may or may not be accurate or representative of the objective ability (Bouffard-Bouchard, Parent, & Larivée, 1991). However, a strong self-efficacy appraisal is an essential condition for success and perseverance in a science program (Maehr, 1983).

One aspect of metacognition, the accuracy of the students' level of confidence in the robustness of their plans and exactness of solutions, was investigated. It appeared that most students tended to slightly overestimate their plans and/or solutions. In the light of Bandura's (1986) work, the consequences of this minor misjudgement of self-efficacy is not worrisome in regard to the students' motivation and retention in the long run. People with marked underestimation of their self-efficacy are more at risk than those who overestimate their potential. Even though the "over-estimators" will eventually have to revise down their judgements toward more appropriate ones, in the face of failures or obvious difficulties, their overall motivation and perseverance is likely to be less undermined than that of the systematic "under-estimators."

Students' Cognitive Processes

"Most physics instructors, however, hope not only that their students will become familiar with the established body of knowledge, but that they will also develop abilities and inclinations to *think like physicists*" (Hammer, 1996, p. 1319). Thinking like a physicist involves relying heavily on the use of cognitive processes such as metacognition and problem-solving. This study provided insights into participants' cognitive processes and problem-solving abilities and this leads to further thinking on how instructional practices can best foster the development of such desirable competencies.

Metacognition

The survey indicated that students are strategic in preparing for exams and problem-solving assignments. The nature of the strategies suggests that students choose the approach that best prepares them for exams. This is most likely a function of what actually happens. The message they seem to deduce from the system is that grades are important and, as a result, they quickly master approaches that yield the best results in exams. This is consistent with the observations of Dickie (2003) who noted that the intellectual skills rehearsed by physics students at the college level depended on the cognitive demands of the task they were asked to undertake. This has also been observed by Crooks (1988) in his conclusion on how assessment influences students' perception of what needs to be learned and how this affects student motivation and their approaches to studying.

The intentionality and conscious efforts require students to anticipate what they will be tested on so they can prepare themselves in the best way they can has a strong metacognitive connotation. The PBL intervention showed that cognitive actions that are related to metacognition (e.g., 'testing conditions for the application of a procedure' and 'evaluating results') were among the cognitive actions most often invoked by the students while solving a problem in a PBL context.

These results suggest a strong potential for developing metacognitive skills and monitoring among the students. However, once out of a "controlled" or known environment or when left on their own, some students "freeze" in the face of unfamiliar tasks. This is what the results of the pre- and post-test suggest. Many students displayed limited metacognitive abilities in the problem sets (pre- and/or post-tests), even though the problems had been tailored to their level by the researcher and controlled by their professor so they would represent a reasonable task. Whenever they were confronted with an unusual or challenging situation, it appeared that some students were so unsettled that they could not use or display the metacognitive and critical thinking resources and potential they would normally use in more familiar and comfortable situations. From this perspective, developing metacognition among physics students appears highly desirable. Ganz and Ganz (1990) support this viewpoint and indicate that metacognition has the potential to empower students to take charge of their own learning, increase their perceived self-efficacy, and decrease the potential for learned helplessness.

The question that naturally follows is that given the predisposition of students for metacognitive and integrative actions, why are these capabilities not displayed and utilized more broadly by students? Is it possible that the current instructional contexts leave little room for this potential to be nurtured? Instructional practices need to be examined in this light, in order to identify what are possible ways in which the metacognitive and integrative potential of undergraduate students in physics could be developed and built on. One possible trend is Koch's (2001) suggestion that metacognitive training be applied in teaching reading comprehension of physics texts as an effective self-monitoring device for students.

Problem-solving

The results of the survey related to rote memorization of formulas and equations are consistent with the findings of Dickie (2003), who concluded that most students at the college level approach physics with the intention of memorizing formulas rather than understanding concepts. This raises serious questions about the message conveyed in physics courses and what is actually expected of students when solving problems during exams. Of course, just as in any domain, minimal facts and information must be acquired in physics and this is mainly done through memorization. But there is also the question of how dependant on remembering such facts the students become when tackling novel problems. For example, can some equations be derived or at least approximated if the students have a robust understanding of the underlying principles rather than only a superficial recollection of formulae without a clear understanding of how and when to use them.

In a critical review, D. N. Perkins and Salomon (1989) exposed how, despite numerous efforts to refashion themselves, most educational practitioners remain committed to imparting facts and algorithms and, in doing so, "educating memories" instead of "educating minds." This leads to the autonomy in thinking issue. Do we prepare students to use facts and play with them instead of simply memorizing them and being bound by them? Is this explicitly modelled by instructors or is it simply expected of students?

Newell and Simon (1972) defined planning as the hierarchical and sequential organization of goals and sub-goals representing a course of action. Most physics students are not used to planning before solving problems. They are not clear on what they should do to actually plan, even when they are asked to write down and justify every step they intend to go through in solving a problem. Breaking down a complex task into small units is not easy but it can be learned and practiced. The results of the present study actually suggest that a single opportunity to practice planning before solving problems (the pre-test itself constituted such an opportunity in the context of this study) was enough to induce an overall and significant improvement of the problem-solving scores in the post-test.

Thus, it is particularly interesting, from an instructional perspective, to observe that one single exposure to a specific approach to problem-solving, even with little guidance (i.e., only asking the students to plan and think back on their solution in the pre-test) can actually result in superior results in the post-test. This suggests that systematic and structured modelling and training in planning good and strategic solutions would likely produce excellent results and, most of all, empower the students and help them develop greater autonomy when solving problems, particularly when faced with unfamiliar and challenging ones.

Instructional Contexts

Two instructional contexts were of particular interest in this study: the traditional teaching of physics and the PBL approach. As results indicate, both contexts have strengths and limitations and this section is an opportunity to address the potential of each in facilitating physics learning and to raise a number of related questions.

Potential of Traditional Instruction

During particularly complex demonstrations, the traditional professor usually announced what difficulties might arise or which potential caveats should be avoided when using the resulting equations. He often modeled out loud his reasoning as he went along. How could such expert modeling be displayed consistently in all lectures to ensure that students are exposed to all aspects of the reasoning and problem-solving capacities of their professor more systematically?

Given the openness of the professor to questions and the fact that he prompted students to ask questions, the actual observed level of students' participation may appear surprisingly low. Possible explanations for persistent low levels of participation are proposed here. First, the rapid pace and dense content possibly leave little time or space for questions. "Understanding" and "teaching" often do not happen at the same time in physics. The concepts addressed are complex and require of most students to read and process the information at a later time. Few students can follow the pace and readily interact with the professor to discuss the topics being presented or fine-tune their understanding in the classroom.

What was frequently observed by the researcher and confirmed by the professor in the interview was that students come to class with questions and want to ask their questions at the beginning of the class. Because of time limitations and a looming lecture ahead, not all questions get answered. Such a situation raises the recurrent debate between quantity and quality in science teaching. Is it better to cover more topics, even superficially? Or is it better to cover less to guarantee a deeper understanding and instead, dedicate time to entertain students' questions? Is covering more occurring at the expense of the quality and depth of the learning? In the long run, the advantages of either choice are not that obvious. When using Peer Instruction in algebra-based introductory physics courses, Crouch and Mazur's (2001) recommendation is to reduce the number of topics covered in the semester in order to accommodate an in-dept approach. However, they conclude that the best approach depends on the students' abilities and the goals of the course. Based on their findings, Angell, Guttersrud, Henriksen, and Isnes (2004) advise from a general perspective that the number of topics covered be cut in physics curricula in order to keep students already enrolled in science and technology programs as well as to attract new students.

Potential of PBL

It looks promising to see that a short experience in a PBL approach to problem-solving can trigger the students' physical intuition and increase their self-efficacy when faced with unfamiliar and complex tasks. The successful and positive outcome achieved during the PBL activities likely contributed to reinforcing the PBL students' confidence in their capability and skill to deal with novel situations.

In a study using PBL for half of their participants and non-PBL courses for the other half, Hmelo, Gotterer, and Bransford (1997) asked medical students at the end of a case what they would want to learn more about to better understand the case and how they would go about meeting their learning needs. It can be noted that this is a similar approach in nature to the questions asked in this study as a part of the second problem of both the pre- and post-test (i.e., students were prompted to identify the gaps in their knowledge and/or missing information in the problem statement that prevented them from solving it). Hmelo et al. (1997) coded written responses for coherence, reasoning strategies, use of science concepts, self-directed learning, and problem-solving strategies. Their results showed that the PBL students were in general significantly more effective in using hypothesis-driven reasoning (as they were taught) when solving problem than the non-PBL students who were more likely to use data-driven reasoning strategies. These results suggest that cognitive measures can play a meaningful role in the assessment of students' learning and that PBL has the potential to foster the development of such desirable abilities. In medical education, PBL has become much more mainstream (Camp, 1996; Antephol & Herzig, 1999) and it can be hypothesized that this tendency will continue to spread in other science programs such as physics that have been traditionally lecture-based.

PBL vs. Lecture

A number of authors have compared formal traditional and PBL instructional contexts and obtained superior results in some cases in the PBL group. Bloom (1984) specifically compared conventional teaching and tutoring and concluded that an average student under tutoring was about two standard deviations above the average student of the control class in the final achievement measure he designed. He attributed these results to the differential treatment and interactions in the two contexts: in a tutoring situation, there is constant feedback and because of the small groups, no student is ignored. Capon and Kuhn (2004) concluded that, while two groups of business students (PBL vs. naturalistic environment) showed equivalent results on knowledge acquisition, the PBL group showed a superior ability in explaining and articulating the concepts. The academic achievement of students of two medical schools (one using PBL and the other a more traditional approach) studied by Verhoeven et al. (1998) were not significantly different from one another. The medical knowledge output acquired by both groups was judged equivalent.

These conclusions are compatible with Dochy et al.'s (2003) who also found no significant results when assessing the knowledge of the students who had experienced PBL. However, they noticed a robust positive effect from PBL in the skills of the students and the long term retention of acquired knowledge. This improvement in skills is aligned with one of the findings of this study where the PBL students displayed a significantly superior physical intuition than their peers who had only had exposure to the traditional instructional context. Hmelo et al. (1997) go further and conclude that "cognitive measures can be used to distinguish students who have participated in PBL from their counterparts in terms of knowledge, reasoning, and learning strategies" (p.387).

Both instructional contexts, i.e., traditional teaching and PBL, when looked at from the results of this study's perspective as well as from the viewpoint of the literature on the topic, display powerful potential for the development of complex cognitive skills and problem-solving abilities among physics students. No approach fits all situations and, presumably, a wise mix of the two would be most beneficial for students' learning. More research on the complementary features of both instructional approaches should help design learning environments that are even more conducive to developing robust cognitive capacities.

Original Contribution of the Study

By combining both quantitative and qualitative methodologies, this study took a flexible and diversified perspective on problem-solving among undergraduate physics students. This study provides insight into both the processes involved in and the resulting products of problem-solving, especially when students deal with unfamiliar and challenging problems.

The development of an informative survey, taking into account the specific context and experience of advanced undergraduates to address their approaches to physics learning and perceived role as students, also constitutes an original contribution. The encouraging results obtained with the principal components analysis and reliability analyses suggest that additional phases of validation could successfully be attempted in an effort toward the validation of this instrument. The survey also has the potential to be adapted to provide insight on advanced undergraduates in other science or engineering disciplines.

The development of a systematic approach to assess written problem-solving solutions and to identify the presence and quality of cognitive processes and problem-solving abilities, based on documented indicators, is another original methodological contribution of this study. The scoring system developed in this study is flexible enough to be used in other courses of the physics program or to be adapted to other disciplines where problem-solving exercises are used to assess students' understanding and reasoning. The overall indices defined for metacognition, critical thinking, physical intuition, and problem-solving abilities on a maximum scale of 100 facilitated contrasts between cognitive skills as well as between different conditions of administration. Visual representations of the results can easily be derived and efficiently communicated.

The study provides evidence that short and resource-limited PBL interventions in a lecture-based context can produce positive results in eliciting the cognitive skills and problem-solving abilities of students. This constitutes a promising perspective for physics instructors and traditional institutions who are interested in implementing or considering the progressive usage of more interactive approaches to physics teaching.

Limitations of the Study

The most important limitation of this study is possibly linked to the overall low number of participants it involved. A modest number of cases tends to reduce the power of statistical analyses and calls for nuances in interpretation. This situation also prevents generalizations from being drawn to a larger population.

The impossibility of getting a randomized assignment to either the traditional or PBL group – mostly because of the time consuming nature of the intervention and the need for the PBL participants to commit to all of the activities over the course of one week – is a methodological limitation of this study.

Another limitation is related to the “intensive” format of the PBL activities. Students in a more typical PBL context do not experience this instructional approach only for one week but rather over a full semester or even during their entire program. During such longer periods of time, frustration and de-motivation can occur from time to time. When difficulties arise, even temporarily, they can affect the students’ progress and work. Conflicts among members of a team are not rare in a more typical PBL context and they need to be resolved to preserve the group dynamics and efficiency of the team. For instance, team evaluations can prove trying for some groups of students.

In the context of this study, the students appeared to get along really well at all times, despite the fact that they were not acquainted prior to their participation in the PBL sessions. It is possible that the novelty and limited time exposure to this approach contributed to the high level of motivation and commitment of the PBL participants in this study as well as in maintaining a positive and pleasant atmosphere during the week. The students knew they were participating in an experiment and presumable made every effort to contribute to its success.

The students' motivations for participating were discussed only informally:

(a) Prior to the introductory presentation by the PBL tutor, the PBL students indicated they were interested in exploring new approaches to problem-solving. They appeared receptive to the idea of being participants in a study about their learning. The four of them had already participated in the Phase I of the study by completing the survey and they seemed eager to collaborate again.

(b) During the introductory presentation on PBL, the students had appeared particularly interested in learning that PBL was an existing instructional approach utilized in physics in some institutions and that their tutor was using such an approach on a regular basis in his home institution in Ireland.

(c) After experiencing PBL for the first time, two students inquired whether the study was a pilot preceding a reform of the physics curriculum and programs within which PBL would be included in the near future. The four students mentioned they had enjoyed their experience and expressed the wish that their courses could resemble what they had just experienced more frequently.

This motivational angle and personal perspective on the PBL experience could have been explored had the students been formally interviewed immediately following their participation into the PBL intervention.

With regard to the development of the APL/CORPS survey, although its validation was not the mandate of this study, its robustness would have been increased had it been possible to re-test the survey with a larger sample of students. In an ideal situation, the results to the initial experimental validation, including principal components analysis and reliability analysis, performed with the data from a limited number of participants (i.e., what took place in the context of this study) would have led to a series of measures in an effort toward standardization. For instance, iterations of the following steps would be needed: a) additional revisions of the items of the survey, b) a subsequent re-administration of the survey to a large group of students, c) new analyses, including confirmatory factor analyses and results stability analysis, etc.

Recommendations for Research and Practice

Within any research endeavour, choices have to be made and, as a result, a number of interesting and promising research objects remain not investigated, hypotheses not verified, and question unanswered. This section is an opportunity to suggest additional research options and practice-related adaptations that are worth considering but that have not been pursued in the context of this study.

Practice

In the light of this study's results, the implementation of PBL activities is recommended. Even if the transition is performed only for a module within a traditional lecture course in a traditional department and institution and even with limited resources, positive results beneficial to students can be expected and attained. Schuh and Busey (2001) actually recommend small-scale changes in traditional settings to allow both the instructor and the students to gradually move from a traditional course design toward problem-based learning (e.g., progressively give students more responsibility in their learning process, allow time for the professor to develop complex and comprehensive problems around which they will initiate the transition to PBL). This view is supported by van Kampen et al. (2004) who found increased student motivation and positive implementation results in general after integrating PBL in a single physics module in an otherwise lecture-based curriculum. In the light of their meta-analysis results on the effectiveness of small-group learning in undergraduate science, mathematics, engineering, and technology courses and programs, Springer, Stanne, and Donovan (1999) recommend its widespread implementation at the undergraduate level.

Considering the results of the PBL interventions, it appears that exposing students to unfamiliar and challenging problem situations could be beneficial to foster the development and use of their physical intuition and also to help build a stronger self-confidence in their abilities to tackle challenging problems. It is suggested that such an approach be considered by instructors whether they are operating in a traditional or PBL environment. The regular exposure of students is the key to developing a feeling of increased comfort in the face of learning situations, which at a first glance, can be potentially challenging.

Training professors, research assistants, and students into PBL is necessary for departments and institution wishing to implement PBL into their instructional approach repertoire. For most instructors, a shift from a lecture-based context to a PBL approach causes the individual to experience the challenges inherent in rethinking their entire concept of teaching and learning (Sage & Torp, 1997). Kolmos (2002) insists on the importance for teachers to first alter their views on teaching (from a teacher-centered to a learner-centered approach), reflect on and discuss their views openly with colleagues, if they want to avoid practicing traditional teaching within the framework of a problem-based model of instruction. Redish (1994) sheds an interesting light on why a shift from the traditional lecture approach to teaching is challenging for many physicists: “For those of us who love learning, the experience of lecturing and teaching is such a powerful learning experience that we do not want to give it up, even when it proves less effective for our students than other methods” (p. 799).

The systematic modelling of strategic problem-solving strategies for students in all courses of physics program should be considered in order to assist in the development of expert-like problem-solving abilities. Huffman’s (1997) results indicate that explicit problem-solving instruction improved the quality and completeness of students’ physics representations more than textbook strategy. Leach, Millar, Ryder, and Séré (2000) present science teaching as a process of acculturation of students into the forms of reasoning that pertain to a specific discipline. From that perspective, it appears important for students to observe expert physicists model reasoning and problem-solving as a way to prepare themselves for careers in physics. Metacognitive and critical thinking processes, also highly desirable in physics, should be modelled systematically and intentionally for the same reasons. Such modelling can very well take place in traditional instructional contexts.

Students also need to rethink their roles as learners, especially those who have been successful in more traditional contexts (Torp & Sage, 2002). The transition from the traditional context to PBL in itself can be seen as an educative experience. Savin-Baden (2001) recommends that both students and professors be given an opportunity to acknowledge their sense of loss (i.e., moving away from the comfortable and familiar traditional context) as well as some space to discuss their discomfort as a mechanism to engage in a positive and sustainable change of perspective of one's role in the teaching and learning process.

In addition to both professors and students progressively adapting to changing roles, the institutions need to provide physical environments that are conducive to collaborative learning. Graetz and Goliber (2002) recommend that the successful universities: (a) stop building large lecture halls and plan for small groups of students engaged in discussion, (b) anticipate movement, not just of students and instructors, but of tables, chairs, white boards, data projection, and laptops, and (c) visualize technology as mobile, unobtrusive, and supportive of collaboration versus information delivery.

Research

The problem frame of the microwave PBL problem that was elaborated in this study represented the "expert frame" of the knowledge and procedures (Donin, Bracewell, Frederiksen, & Dillinger, 1992) necessary to solve the problem. This problem frame, which was presented in a hierarchical format, was transposed into "nodes" and "children" in the NVivo software and constituted one of the coding trees subsequently used to code the transcripts of the PBL sessions. In other words, each utterance of the students and tutor could be related to one element or the other of the problem frame depending on what aspect it referred to. Differential results were presented as a function of the session (first or second) and speaker. An interesting complement would consist in tracking the sequence that the PBL students followed when solving the microwave problem to create a 'novice frame'. Although the PBL students did solve the microwave problem successfully, the path and steps they followed were different from the expert model. The students eventually covered most of the problem frame but their procedure was not straightforward. The PBL students' sequence reflected their trials and errors. The trace analysis (Frederiksen & Donin, 1999) of the structure of their problem frame would provide further insight into students' reasoning and the specific procedures they applied to solve the problem. The comparison of the novice frame with the expert model would also highlight potential conceptual and procedural difficulties encountered by students in the context of this study.

In the case of this study, the primary interest was in the "supervised" learning (i.e., when the PBL tutor was present, whether he intervened or not) of the PBL students. Another interesting and complementary sequel to this study would be to investigate the autonomous learning and organization of work of students in a PBL context. From that perspective, video recordings of the students' meeting would provide insight into group dynamics that take place when the students are completely in charge (i.e., unsupervised) of setting the goals and outcomes of their meeting and of monitoring and assessing their own progresses. The potential improvement of their interpersonal capacity to communicate along with the progression of their collaborative knowledge and skills (Kolmos, 1999) could be thus monitored and studied.

As a complement, asking students to keep a log with regards to their self-directed study periods – and if necessary help them develop an appropriate and effective instrument to do so – would inform instructors about the individual strategies and self-directedness of students dealing with ill-defined tasks such as PBL problems.

Another interesting follow up to this study would be to gather participants' perspectives on the PBL intervention to improve the approach in a future implementation of similar activities and to better understand the mechanisms of adaptation the students engaged in, in order to rapidly function in a PBL context even it is their first experience with this instructional approach. From this perspective, Cooper and Robinson's (1998) recommendation that more research on the practices related to small group instruction in science, mathematics, engineering, and technology be conducted to address how groups should be formed, how large they should be, and how long they should stay together appears relevant.

The results of this study suggest that the development of cognitive processes and problem-solving abilities of physics undergraduates can be positively influenced and fostered. Incorporating a large sample in the design would make it possible to generalize findings. More research is needed to capture the essence of these changes and to determine how innovative and interactive approaches such as PBL can contribute and enhance the strengths and accomplishments that are realized in traditional instructional contexts. As Redish and Steinberg (1999) concluded, "the dialog within the physics community on what is effective in instruction is now well begun" (p. 30) and this is most promising.

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APPENDIX A: WRITTEN INVITATION TO PARTICIPATE IN PHASE I OF THE STUDY

INVTATION TO PARTICIPATE IN THE FIRST PHASE OF A STUDY OF THE HIGHER-ORDER THINKING PROCESSES AND PROBLEM-SOLVING ABILITIES OF PHYSICS STUDENTS IN ELECTROMAGNETISM

Dear Student:

I am a Ph.D. student in Educational Psychology at the Centre for University Teaching and Learning here at McGill University. I completed both an undergraduate degree in physics (with coop terms in magnetic fusion) and a masters in educational science (with a specialization in physics teaching) at the University of Sherbrooke. I also completed a physics teaching certificate at the University of Montréal. The subject of my doctoral research concerns the higher-order thinking processes and problem-solving abilities of physics undergraduate students in electromagnetism.

As a part of this study, you will be asked to complete a survey on your approaches to physics learning as a student that should not take more than 45 minutes to fill.

Your professor in this course, Dr. X, kindly accepted to collaborate to this research project. He is willing to welcome me in his classroom and to let me request your participation. Your colleagues, taking the course Electricity and Magnetism (PHYS-340) with Dr. Y, will also be invited to participate in this study.

In addition to knowing that you contributed significantly to research into physics teaching and learning, I hope that you will also gain personal insight through your participation in the study.

Your participation and the data generated in the research will be treated with confidentiality. Your identity will be protected and all records will be coded to guarantee anonymity. Your professor will never see your answers to this survey. The data from this study may be published.

Your collaboration is essential and will be greatly appreciated.

Thank you for your time and consideration.
I am looking forward to meeting you,

Josée Bouchard

APPENDIX B: WRITTEN INVITATION TO PARTICIPATE IN THE PHASE II OF THE STUDY

INVTATION TO PARTICIPATE IN THE SECOND PHASE OF A STUDY OF THE HIGHER-ORDER THINKING PROCESSES AND PROBLEM-SOLVING ABILITIES OF PHYSICS STUDENTS IN ELECTROMAGNETISM

Dear Student:

I am a Ph.D. student in Educational Psychology at the Centre for University Teaching and Learning here at McGill University. I completed both an undergraduate degree in physics (with coop terms in magnetic fusion) and a master's in educational science (with a specialization in physics teaching) at the University of Sherbrooke. I also completed a physics teaching certificate at the University of Montréal. The subject of my doctoral research concerns the higher-order thinking processes and problem-solving abilities of physics undergraduate students in electromagnetism.

The first phase of this study has already been completed in the Fall 2003 semester. If you participated in this first phase, you might recall filling out a survey on your approaches to physics learning and perspectives as a physics student. Whether you have filled the survey or not, you are most welcome to participate in the second phase which will take place during the current semester.

Your professor in this course, Dr. X kindly accepted to collaborate to this research project. He is willing to welcome me in his classroom and to let me request your participation.

With the second phase of this study, students will be asked to participate in two assessments over the semester (winter 2004). Each assessment will last approximately 45 to 50 minutes and will consist of 2 electromagnetism problem-solving exercises.

There will also be a special activity during the week of March 22nd to March 26th, 2004 and I would like to invite you to be a part of it. A professor specialized in physics problem-based learning (PBL) will come from Dublin (Ireland) and bring a special contributibution to this study. During that week, this distinguished guest professor will lead 2 or 3 short sessions of problem-based learning – of about one hour and a half each – on a topic not yet addressed in your current course of electromagnetism. This special activity will focus on problem-solving as a vehicle for learning advanced electromagnetism. It will take place outside of the regular class time so, if you choose to participate, you will not miss any class because of the study.

On each of the two or three days when there will be a PBL session, students selected for this special activity will be provided with a complete meal to compensate for their time. At the end of the week, they will be offered with a gift certificate. These are not the only potential benefits of participating. Students participating in this type of research, in addition to knowing they contributed significantly to research into physics teaching and learning, often find the experience beneficial for many reasons. They get access to alternative teaching approaches and problem-solving strategies. They also derive a better grasp over the concepts dealt with in their course as a result of solving especially designed problems. Moreover, at the end of the research, you will be provided with the complete solutions to all the problems used in the study.

Your participation and the data generated in the study will be treated with confidentiality. Your identity will be protected and all records will be coded to guarantee anonymity. Your professor will never see your answers to any of the assessments. The data from this study may be published.

Your collaboration is essential and will be greatly appreciated. If you are interested in participating in the special problem-based learning activity, please provide the information requested on the back of this form.

Thank you for your time and consideration.

Josée Bouchard
Ph.D. Candidate

PLEASE PRINT

Name: ____________________________________

E-mail Address: ______________________________ and/or

Local Telephone Number: _______________________

Time during the week of March 22nd to March 26th, day or evening, when you would be able to attend and participate in the special electromagnetism problem-based learning (PBL) sessions:

Monday: _________________________
Tuesday: _________________________
Wednesday: _______________________
Thursday: ________________________
Friday: __________________________

Thank you very much!

February 2004

APPENDIX C: INDIVIDUAL E-MAIL INVITATION AND PRESENTATION OF SCHEDULE FOR THE PBL ACTIVITY

Dear Student X:

When I visited your electromagnetism class with Professor Y on February 9th to discuss my study on problem-solving, you indicated that your available time for some Problem-Based Learning (PBL) sessions would be as follows:

Monday: after 12:30 p.m.
Tuesday: 10:00 a.m. to 2:00 p.m. and after 5:00 p.m.
Wednesday: after 12:30 p.m.
Thursday: 10:00 a.m. to 2:00 p.m. and after 5:00 p.m.
Friday: after 12:30 p.m.

I combined this information with what the other students in your class provided in order to accommodate as many of you as possible. We would like to form small groups of 4 to 7 people among you.

After consulting with Professor Z, who will visit from Dublin in March, we would like to present you with the following schedule for the week of March 22nd to March 26th, 2004. As announced, there will be 2 PBL sessions to attend during that week. During those 2 sessions, the PBL tutor will introduce the problem-based learning approach and guide you with its application when solving a specific problem that we will present you with. Instead of a formal 3rd session, we would like you to rather have a short team meeting (only for the members of your small group, i.e., without the tutor being present) to discuss the problem to be solved. And lastly, there would be a final assessment consisting of 2 electromagnetism problems to solve.

Here is concretely what the proposed schedule looks like:

On Monday, March 22nd: You would meet with the tutor **from 1:30 p.m. to 4:30 p.m.** The fist hour or so would serve to introduce the PBL approach (you are not expected to know anything about it). Then, we will form small groups of about 4 to 7 people each among you. The remaining time will be for the actual first PBL session. To thank you for your time, you will be provided with dinner at the end of this first session.

On Tuesday, March 23rd: You would meet with the other members of your small group **for about 1 hour** – anytime between 10:30 a.m. and 12:30 p.m. (noon) -- to discuss the problem to be solved without the tutor being present. On that occasion, you will be served with a light snack.

On Wednesday, March 24th: There is **no formal meeting** on that day but it is recommended that you dedicate some time to personal or self-directed study to be ready for the 2nd PBL session, say 30 minutes to one hour on your own.

For your information, Professor Z will present a public conference on PBL in physics from 1:00-4:00 p.m. on that day in room XX of the Physics Building. This conference is not linked to your participation in the study so you are under no obligation whatsoever to be present. However, you are most welcome to attend if it interests you.

On Thursday, March 25th: You would meet with the tutor **from 11:00 a.m. to 1:00 p.m.** for the second and last PBL session. You will be served with a lunch meal around noon.

On Friday, March 26th: You would complete an assessment consisting of 2 electromagnetism problems to solve that should take you about an hour, starting at 2:00 p.m. As a token of our appreciation for your participation in the study -- more specifically for the 2 PBL sessions, the small group meeting, and completing the final assessment -- you will be offered with a $20. gift certificate.

I wish I could give you even more to acknowledge your time and valuable contribution to the study but I am myself still a student. :)

Student X, the available time slots you indicated are fortunately entirely compatible with our study's planning so I do hope that you will seriously consider becoming a participant.

Please note that, to ensure the validity of the data collected in this study, it is important that you commit for the 4 activities to take place in the week of March 22nd to March 26th (i.e., the 2 PBL sessions, the small group meeting and the assignment) if you want to be selected as a participant.

Please let me know before Friday, February 27th whether you are interested or not in participating, given the schedule presented above. I thank you very much for your time and consideration and hope that you will accept to participate. I look forward to your reply.

I take this opportunity to wish you every success for the current exam period.

Best regards,
Josée Bouchard

P.S. Do not hesitate to contact me if you have any questions. Also, if you know a classmate who was absent when I visited your class the other day and who might be interested, please invite him or her to e-mail me. Many thanks.

APPENDIX D: ELECTRONIC INVITATION TO BECOME A GRADUATE STUDENT REVIEWER

Dear Graduate Student,

I am a Ph.D. candidate at the Centre for University Teaching and Learning (CUTL) at McGill University. My background is in physics and, in my thesis, I address higher-order thinking processes and problem-solving abilities of undergraduate physics students in advanced electromagnetism courses.

My dissertation takes place under the supervision of Professor Alenoush Saroyan. Professor Richard (Dik) Harris, of the Department of Physics, is a member of my thesis committee.

I am writing to you to request your collaboration in validating some of my instruments for my data collections, i.e., a survey and a problem set. Your role would be to provide comments on the clarity and the relevance of the items, not to actually answer the questionnaire or to solve any problems.

Simply, for the purposes of my project, I need some independent opinions from experienced students in physics. It should take you about 2 hours to review the 2 instruments. I will come to the Department of Physics at a time and date that are convenient to you. Your collaboration is extremely valuable and will make a significant contribution to the research.

Your reply before next Wednesday would be most appreciated. I am looking forward to your message.

Thank you very much and best wishes for a successful semester.

Josee Bouchard

Josée Bouchard, B.Sc., M.A.
Ph.D. Candidate
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McGill University
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Montreal, QC
H3A 1Y2

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E-mail: ***josee.bouchard@mail.mcgill.ca***

APPENDIX E: CONSENT FORM FOR THE GRADUATE STUDENT REVIEWERS

McGill

Students' Approaches to Learning
and Higher-order Thinking in Solving Physics Problems

Graduate Student Consent Form
(Instruments Validation)

I agree to participate in this doctoral dissertation research conducted by Josée Bouchard under the supervision of Dr. Alenoush Saroyan of the Centre for University Teaching and Learning (CUTL) and the Department of Educational and Counselling Psychology at McGill University.

I understand that the main purpose of this investigation is to study physics undergraduate students' approaches to learning, their higher-order thinking processes along with their problem-solving abilities when solving electromagnetism problems.

I understand that my role in the study will include reviewing the two following instruments designed by the researcher at two different dates: a) a survey on the students' approaches to physics learning and perceived role as a physics student and b) a problem set template on electromagnetism. As a physics graduate student, I will provide insights and written comments to the researcher about the clarity (for a undergraduate student) and the relevance (in the research project) of the various items of the instruments I will be asked to review.

I understand that reviewing and commenting on one instrument should last approximately one hour and thirty minutes.

I understand that my participation and the data generated in the study will be treated with confidentiality. My identity will be protected. The researcher will use the data to evaluate and revise her instruments.

I understand that the data from this study may be published.

I have voluntarily agreed to participate in this research and understand that I may withdraw at my own discretion and for any reason at any time.

Name (please print): ______________________________

Signature: ______________________________________

Date: ____

APPENDIX F: EXCERPT OF THE APL/CORPS VALIDATION INSTRUMENT

Clarity: 1 2 3 4
Relev. : 1 2 3 4

2H2. How important is it for you to get high grades this year?

(1) Of no importance
(2) Of some importance
(3) Of moderate importance
(4) Of high importance
(5) Of very high importance

Comments and/or suggestions as a reviewer: ______________________________

Lessons learned from their previous year(s) in their program

Clarity: 1 2 3 4
Relev. : 1 2 3 4

2I1. What are some of the lessons learned from your previous year(s) in your current program? Describe two (2) lessons you derived from your academic experience in your current program. Then for each lesson, say what you do or think of differently now, if anything, as a result.

Lesson 1: ______________________________

Lesson 2: ______________________________

Comments and/or suggestions as a reviewer: ______________________________

APPENDIX G: EXAMPLE EXTRACTED FROM THE APL/CORPS VALIDATION AND DECISION MATRIX

				Grad Stud 1		Grad Stud 2		Grad Stud 3		Grad Stud 4		Grad Stud 5				
Dimension	**Category**	**Item code**	**Type of item**	**Clarity Score G1**	**Relev Score G1**	**Clarity Score G2**	**Relev Score G2**	**Clarity Score G3**	**Relev Score G3**	**Clarity Score G4**	**Relev Score G4**	**Clarity Score G5**	**Relev Score G5**	**# of grads found not clear**	**# of grads found not relevant**	**Decision**
Pers. Exp.	Comfort Program	1A1	L5	4	4	4	4	4	4	3	4	3	4	**0**	**0**	√
Pers. Exp.	Confort Interact. w/ Profs	1C2	L7	4	2	2	4	4	4	3	3	4	4	[illegible]	[illegible]	**Modif**
Pers. Exp.	Streng./weak.	1D2	L5	4	2	4	4	4	4	3	4	3	3	**0**	1	√
Pers. Exp.	Streng./weak.	1D3	L7	4	4	4	4	2	4	2	2	2	3	3	1	**X**
Perspect. Learn.	Career	3H1	SA	4	4	4	4	4	4	4	4	3	3	0	0	√
Role & Pa Particip.	Small-group	4E1	O	4	4	4	4	4	4	4	4	3	3	0	0	√

<u>Legend</u>

▨ Indicate that an explicit comment was specifically made about the clarity or the relevance (depending in which column the highlighted cell is) by a given reviewer. For readability purposes, the actual comments provided by the reviewers have not been included in the above excerpt.

■ Indicate that one or more graduate student reviewer(s) found the item unclear or not relevant (depending in which column the highlighted cell is).

✓ Indicate that an item was maintained in its original format.
Modif. Indicate that an item was modified to reflect the suggestions and comments provided by the graduate student reviewer(s).
✘ Indicate an item that was removed from the questionnaire.

APPENDIX H: STRUCTURE OF THE SECOND VERSION OF THE APL/CORPS

(as administered to the participants)

Dimension	Category	Nb. of Items
1- Personal Experience of their Current Physics Program	1A. Level of comfort in their program	2
	1C. Degree of comfort when interacting with their instructors	1
	1D. Perceptions of their strengths and weaknesses as physics students	3
	1E. Degree of commitment and self-discipline	3
2- Academic Experience of their Current Physics Program	2A. Personal learning goals	3
	2B. Study and homework habits	4
	2C. Preparation for exams and evaluations	5
	2E. Metacognitive skills	4
	2F. Critical thinking	5
	2G. Links — perceived (or not) — between the different courses of their program	2
	2H. Importance of grades	2
	2I. Lessons learned from their previous year(s) in their program	1
3- Perspective on Physics Learning	3B. Conceptions of "truths" and "facts" in physics	2
	3C. Cognitive and intellectual abilities perceived as important for studying physics	4
	3D. Personal definition of what studying/learning physics is about	4
	3E. Perceived importance of learning about physics in their lives	4
	3F. Perception of the contribution of research to the field	2
	3G. Degree of willingness to challenge accepted views and positions	1
	3H. Careers and professional options they envision for themselves	3
4- Role and participation in the classroom, as a physics student	4A. Nature and degree of students' participation in the classroom	2
	4B. Perception of what is expected of them in the classroom	1
	4C. Comfort about asking questions or engaging in discussions	3
	4D. Preferred mode(s) of learning	1
	4E. Interest for small-group learning activities	1
Demographical Information	N/A	10
	Total	**73**

Note: The coding of the categories established in the preliminary version was maintained in the final version to ensure an easier and more reliable correspondence between the two versions of the questionnaire during its validation. Consequently, it is possible that a given category appears missing (e.g., 1B) from the structure of the second version. It indicates that no item remained within that initial category, following the validation of the preliminary version with the graduate student reviewer.

APPENDIX I: APPROACHES TO PHYSICS LEARNING AND CONCEPTIONS OF ONE'S ROLE AS A PHYSICS STUDENT QUESTIONNAIRE

Approaches to Physics Learning and Conceptions of One's Role as a Physics Student Questionnaire

Josée Bouchard
Centre for University Teaching and Learning
McGill University

This survey has been developed as part of a doctoral thesis study and is intended to gather information about your personal and academic experiences of your current physics programs, your perspectives on physics learning, and your perceived role and participation in the classroom as a physics undergraduate student. Your participation in completing this questionnaire is very important and will make a valuable contribution to the research. It should take you approximately 35 minutes to complete this survey.

Confidentiality of Responses

Please be assured that only the researcher will have access to the personal information gathered from individual students. No information that might identify you as an individual will be shared with anyone.

Instructions

- Please record your responses directly on this questionnaire.
- The first 10 items of the survey pertain to demographic information.
- There are no right or wrong answers in such a questionnaire. Your honesty and assistance in completing this survey is greatly appreciated.

Thank you very much for your participation to the study!

Best wishes for a successful semester!

APL/CORPS Questionnaire **Page 1**

1. Please indicate the course number for the class in which you received this questionnaire.
   (1) Electricity and Magnetism (PHYS-340A)
   (2) Electromagnetism (PHYS-350A)

2. What program are you currently enrolled in?
   (1) Major – Physics
   (2) Major – Physics & Atmospheric Sciences
   (3) Major – Physics & Computer Science
   (4) Major – Physics & Geophysics
   (5) Major – Physics & Physiology
   (6) Major – Chemistry & Physics for Teachers
   (7) Major – Mathematics & Physics for Teachers
   (8) Honours – Physics
   (9) Honours – Physics & Chemistry
   (10) Honours – Physics & Mathematics
   (11) Honours – Mathematics
   (12) Honours – Applied Mathematics
   (13) Honours – Engineering (Please specify: ______________________)
   (14) Other (Please specify: ______________________________)

3. In what year?
   (1) U0
   (2) U1
   (3) U2
   (4) U3
   (5) Other (Please specify: ______________________________)

4. Please indicate your gender.
   (1) Female
   (2) Male

5. Which of the following categories most accurately reflects your age?
   (1) 17-18 years
   (2) 19-20 years
   (3) 21-22 years
   (4) 23-24 years
   (5) 25 years or older

6. What is your mother tongue?
   (1) English
   (2) French
   (3) Other (Please specify: ______________________________)

Please continue on the next page.

7. Did you enter your current program at McGill University from:
   (1) High school?
   (2) Cégep?
   (3) Another university or college?

8. In what program were you enrolled at this same former institution (high school, Cégep, university or college) and what degree did you complete there?
   Program: ____
   Degree: ____

9. What was your Grade Point Average (GPA) in this program?
   (1) 0 - 1.00
   (2) 1.01 - 1.49
   (3) 1.50 - 1.99
   (4) 2.00 - 2.49
   (5) 2.50 - 2.99
   (6) 3.00 - 3.49
   (7) 3.50 - 4.00
   (8) I do not know

10. Which of the following best describes where you lived prior to enrolling at McGill?
    (1) Québec
    (2) Ontario
    (3) Atlantic Provinces
    (4) Western Canada
    (5) Country other than Canada (Please specify: ________________________)

11. How certain are you that your current choice of program of study is the best one for you?
    (1) Very uncertain
    (2) Somewhat uncertain
    (3) Neutral
    (4) Somewhat certain
    (5) Very certain

12. Which contexts do you prefer to learn physics? Choose two of the following and then say why on the next page.
    (1) When professors give a lecture
    (2) When I conduct a laboratory experiment
    (3) Alone reading a textbook or a research paper
    (4) Solving problems at home
    (5) Solving problems in a tutorial
    (6) Discussing about concepts and phenomena with classmates
    (7) Other: (Please specify) ____

Please continue on the next page.

My favorite context is________ because ____________________________________

____

My second preferred context is __________ because __________________________

____

13. As an undergraduate student in physics, what do you think your strengths and weaknesses to be? Write down three (3) of each.

Strengths	Weaknesses
____________________________	______________________________
____________________________	______________________________
____________________________	______________________________

14. How would you rate the degree of the students' participation in your physics classes this year? If you think that most students are active participants, choose 7, if most students almost never participate, choose 1. If the students' participation is somewhere in between, find the number that best describes the situation.

Most students almost never participate in our courses						Most students are active participants in our courses
(1)	(2)	(3)	(4)	(5)	(6)	(7)

15. Using a similar scale, how would you rate your own participation in your physics classes this year?

I almost never participate in our courses						I am an active participant in our courses
(1)	(2)	(3)	(4)	(5)	(6)	(7)

16. What kind of students' participation do you think your professors expect from you in the classroom? Explain.

____

____

____

Please continue on the next page.

17. Which of the following statements best fits your view? To be successful in physics…
    (1) Hard work is much more important than inborn natural ability.
    (2) Hard work is a little more important than natural ability.
    (3) Natural ability and hard work are equally important.
    (4) Natural ability is a little more important than hard work.
    (5) Natural ability is much more important than hard work.

18. How does working in a group or a team helps you (or not) to learn physics? When answering, you might want to think of laboratories, assignments, small group activities, etc.

    ____

    ____

    ____

    ____

19. How important is it for you to get high grades this year?
    (1) Of no importance
    (2) Of some importance
    (3) Of moderate importance
    (4) Of high importance
    (5) Of very high importance

20. What are some of the lessons learned from your previous year(s) in your current program? Describe two (2) lessons you derived from your academic experience in your current program. Then for each lesson, say what you do or think of differently now, if anything, as a result.

    Lesson 1: ______________________________________

    ____

    ____

    ____

    Lesson 2: ______________________________________

    ____

    ____

    ____

Please continue on the next page.

21. By indicating numbers from 1 to 5 in the parentheses, rank the following skills in order of importance (1 being the most important for you, 2 the second, etc.).

Please note: If you find that one or many important skills are missing, phrase them yourself using the blank spaces as needed and do not forget to rank them. Also, if you find that one or many skills listed below are not among your top five, do rank them at all. Rank only the five (5) most important skills for you.

The 5 main skills I want to get out of my physics courses this year are:
( ) learning how to reason logically about the physical world
( ) learning how to solve physics problems
( ) learning how to use and operate specialized apparatus and instruments
( ) learning advanced mathematical methods and tools
( ) learning major theories and laws of my domain
( ) learning how to derive and prove major formulas and equations
( ) ____
( ) ____
( ) ____

For each of the following items, read the statement and indicate the answer which is most characteristic of you. Please refer to the scale below to select your answers.

(1) Never or rarely
(2) Occasionally
(3) Sometimes
(4) Usually
(5) Almost always

22. I find it difficult to complete my assignments in physics this year.
(1) (2) (3) (4) (5)

23. I have problems with taking organized class notes in physics.
(1) (2) (3) (4) (5)

24. I work very hard to get good grades in physics this year.
(1) (2) (3) (4) (5)

25. Even when I am tired, I try to complete my assignments in physics this year.
(1) (2) (3) (4) (5)

26. I set high standards for myself in my physics classes this year.
(1) (2) (3) (4) (5)

Please continue on the next page.

For each of the following items, please continue to refer to this same scale.

(1) Never or rarely
(2) Occasionally
(3) Sometimes
(4) Usually
(5) Almost always

27. In physics, I review my notes before the next class.
(1) (2) (3) (4) (5)

28. When preparing for a physics exam, I try to anticipate the questions that I think might be included and study them.
(1) (2) (3) (4) (5)

29. In physics, I try to see the relationships between what I'm studying and what I already know.
(1) (2) (3) (4) (5)

30. In the two (2) following items, you will read a short discussion between two students who disagree about some issue. Then you will indicate whether you agree with one student or the other and why. You can also phrase your personal opinion in your own words if you have a different perspective from those presented.

Brian: I like the way physics explains how things work in the real world.

Vincent: Is research in physics really so useful, anyway? In physics classes, we always look at things that science can explain. But there's lots of stuff that science can't explain – and I'm not just talking about UFOs or miracles.

Brian: I still think that physics applies to almost all real-world experiences. If we can't figure out how, it's because the stuff is very complicated, or because we don't know enough science yet.

Which of the following choices best represents what you think?
(1) I agree almost entirely with Brian.
(2) I agree more with Brian, but I think that Vincent makes some good points.
(3) I agree (or disagree) equally with Brian and Vincent.
(4) I agree more with Vincent, but I think that Brian makes some good points.
(5) I agree almost entirely with Vincent.
(6) I rather think that (please specify): ______________________________

____

____

Please continue on the next page.

If you chose an opinion on Brian and Vincent's discussion among the numbers from 1 to 5, explain why you picked it.

____

____

____

31. **Marian**: Scientific knowledge is manmade but reflects nature as it is. Laws exist with nature whether there are humans observing nature or not. It is only a matter of time until scientific knowledge is the truth.

Paula: I rather think that truth is relative and absolute truth does not exist. Science is based on presumptions and only tries to explain natural phenomena; this is why humans construct laws and theories. Science is only a partial view of nature.

Marian: I don't agree, science like physics is based on facts and it presents an objective view of nature.

Which of the following choices best represents what you think?
(1) I agree almost entirely with Marian.
(2) I agree more with Marian, but I think that Paula makes some good points.
(3) I agree (or disagree) equally with Marian and Paula.
(4) I agree more with Paula, but I think that Marian makes some good points.
(5) I agree almost entirely with Paula.
(6) I rather think that (please specify): ____________________________

____

____

If you chose an opinion on Marian and Paula's discussion among the numbers from 1 to 5, explain why you picked it.

____

____

____

Please continue on the next page.

For each of the following items, read the statement and indicate the answer that best describes how strongly you agree or disagree. Please refer to the scale below to select your answers.

(1) Strongly disagree
(2) Somewhat disagree
(3) Neutral
(4) Somewhat agree
(5) Strongly agree

32. The most crucial thing in solving a physics problem is finding the right equation to use.
(1) (2) (3) (4) (5)

33. When learning physics, a student cannot fully understand new material unless she/he relates it to something she/he already knows.
(1) (2) (3) (4) (5)

34. A significant problem this year in physics is being able to memorize all the information I need to know.
(1) (2) (3) (4) (5)

35. The best way for me to learn physics is by solving many problems rather than by carefully analyzing a few in details.
(1) (2) (3) (4) (5)

36. Only very few specially qualified people are capable of really understanding physics.
(1) (2) (3) (4) (5)

37. "Understanding" physics basically means being able to recall something you've read or been shown.
(1) (2) (3) (4) (5)

38. In doing a physics problem, if my calculation gives a result that differs significantly from what I expect, I'd have to trust the calculation.
(1) (2) (3) (4) (5)

39. In physics this year, I do not expect to understand equations in an intuitive sense; most must simply be taken as given.
(1) (2) (3) (4) (5)

40. Learning physics made me change some of my ideas about how the physical world works.
(1) (2) (3) (4) (5)

Please continue on the next page.

For each of the following items, please continue to refer to this same scale.

(1) Strongly disagree
(2) Somewhat disagree
(3) Neutral
(4) Somewhat agree
(5) Strongly agree

41. If I don't remember a particular equation needed for a problem in a physics exam there's nothing much I can do (legally!) to come up with it.
(1) (2) (3) (4) (5)

42. To understand physics, I sometimes think about my personal experiences and relate them to the topic being analyzed.
(1) (2) (3) (4) (5)

43. A good understanding of physics is necessary for me to achieve my career goals. Good grades in my physics courses this year are not enough.
(1) (2) (3) (4) (5)

44. Learning physics requires that I substantially rethink, restructure, and reorganize the information that I am given in class and/or in the textbook.
(1) (2) (3) (4) (5)

45. Physical laws have little relation to what I experience in the real world.
(1) (2) (3) (4) (5)

46. Scientists are having trouble predicting and explaining the behaviour of thunder storms. This could be because thunder storms behave according to a very complicated or hard-to-apply set of rules. Or, that could be because thunder storms don't behave consistently according to any set if rules, no matter how complicated and complete that set of rules is. In general, why do scientists sometimes have trouble explaining things? Please read all options before choosing one.

(1) Although things behave in accordance with rules, those rules are often complicated, hard to apply, or not fully known.
(2) Some things just don't behave according to a consistent set of rules.
(3) Most of the time, it's because the rules are complicated, hard to apply, or unknown; but sometimes it's because the thing doesn't follow rules.
(4) About half the time, it's because the rules are complicated, hard to apply, or unknown; and half the time, it's because the thing doesn't follow rules.
(5) Most if the time it's because the thing doesn't follow rules; but sometimes it's because the rules are complicated, hard to apply, or unknown.

Please continue on the next page.

47. Are you considering graduate studies at this point in your current program? If so, in what domain?

    ____

48. What kind of career and professional options do you envision for yourself?

    ____

    ____

    ____

49. How many times did you go to your professor(s) for help with your physics course work this year.
    (1) I never went to see any professor this year so far
    (2) One or two times
    (3) Three to five times
    (4) Six to ten times
    (5) Eleven or more time

For each of the following items, read the statement and indicate the answer that best describes how you study for your physics classes. If you think the statement is very true of you, choose 7, if the statement is not at all true of you, choose 1. If the statement is more or less true of you, find the number between 1 and 7 that best describes you. To do so, you can refer to the following scale:

Not at all true of me						Very true of me
(1)	(2)	(3)	(4)	(5)	(6)	(7)

50. In physics this year, I prefer course work that is challenging so I can learn new things.
    (1) (2) (3) (4) (5) (6) (7)

51. I believe that people would think less of me if I got help in order to succeed in my physics courses this year.
    (1) (2) (3) (4) (5) (6) (7)

52. I make sure that I keep up with the physics weekly readings and assignments this year.
    (1) (2) (3) (4) (5) (6) (7)

Please continue on the next page.

For each of the following items, please continue to refer to this same scale.

Not at all true of me						Very true of me
(1)	(2)	(3)	(4)	(5)	(6)	(7)

53. I rarely find time to review my notes or readings in physics before an exam this year.
(1) (2) (3) (4) (5) (6) (7)

54. When studying for an exam in physics, I often explain the material to a friend or classmate.
(1) (2) (3) (4) (5) (6) (7)

55. When I study physics, I set goals for myself in order to direct my activities and make the best out of each study period.
(1) (2) (3) (4) (5) (6) (7)

56. When I am studying for my physics courses this year, I try to determine which concepts I don't understand well.
(1) (2) (3) (4) (5) (6) (7)

57. When course work is difficult in physics, I either give up or only study the easy parts.
(1) (2) (3) (4) (5) (6) (7)

58. When studying for an exam in physics, I memorize formulas and equations.
(1) (2) (3) (4) (5) (6) (7)

59. I try to develop my own understanding of physics topics, rather than only rely on the instructors' ideas.
(1) (2) (3) (4) (5) (6) (7)

60. I try to relate concepts and material learned in one physics course this year to those in other courses of my program, whenever possible.
(1) (2) (3) (4) (5) (6) (7)

61. In physics this year, I prefer easy and familiar course material so I can get good grades.
(1) (2) (3) (4) (5) (6) (7)

62. I rarely see any relationships between material covered in my physics courses this year and other aspects of my life.
(1) (2) (3) (4) (5) (6) (7)

Please continue on the next page.

For each of the following items, please continue to refer to this same scale.

Not at all true of me						Very true of me
(1)	(2)	(3)	(4)	(5)	(6)	(7)

63. When a theory, interpretation, or conclusion is presented in class or readings in physics this year, I try to decide if there is good supporting evidence.
(1) (2) (3) (4) (5) (6) (7)

64. I often find that I have been reading for class in physics this year but don't know what it was all about.
(1) (2) (3) (4) (5) (6) (7)

65. I work on practice exercises and end of chapter problems even if they are not required.
(1) (2) (3) (4) (5) (6) (7)

66. I ask the professor to clarify physics concepts if I don't understand well.
(1) (2) (3) (4) (5) (6) (7)

67. I often find myself questioning things I hear or read this year in physics to decide if I find them convincing.
(1) (2) (3) (4) (5) (6) (7)

68. When I can't understand the material in my physics courses this year, I ask another student for help.
(1) (2) (3) (4) (5) (6) (7)

69. When I study for my physics courses this year, I make charts, diagrams, or tables to help me organize or summarize the course material.
(1) (2) (3) (4) (5) (6) (7)

70. When confronted with difficult material or problems in physics this year, I try to think up possible solutions and then systematically check them out.
(1) (2) (3) (4) (5) (6) (7)

71. When studying for an exam in physics, I practice solving problems similar to what I expect to get in the test.
(1) (2) (3) (4) (5) (6) (7)

72. If I get confused taking notes in physics lectures this year, I make sure to sort it out after class.
(1) (2) (3) (4) (5) (6) (7)

Please continue on the next page.

73. Which of the following best describes how you feel about your current program of study?
    (1) I feel very uncomfortable in my current program
    (2) I feel somewhat uncomfortable in my current program
    (3) I feel somewhat comfortable in my current program
    (4) I feel very comfortable in my current program

This is the end of the survey.
Thank you very much for your assistance and valuable contribution.

APPENDIX J: EXCERPT OF THE PROBLEM-SOLVING TEMPLATES VALIDATION INSTRUMENT

These three higher-order thinking processes are closely linked to a more global and particularly complex one, namely problem-solving. Hence, all the indicators that have just been detailed for metacognition, critical thinking, and physical intuition are all desirable abilities for effective problem-solving. Additional elements are also going to be looked at carefully, such as:

- the students' ability to accurately recognize and acknowledge the relevant assumptions, if any, that should be made in the particular context of the problem;
- their ability to translate or represent the problem into a graphical form, a sketch, or a pictorial representation (Van Heuvelen, 1991);
- their ability to translate verbal or written statements into the language of mathematics (Larkin et al., 1980) and to develop an accurate physical representation of the problem (Maloney, 1994);
- the overall quality, completeness, and accuracy of their solution (including possible evidence of multiple trial-and-error attempts and evaluation of alternative solutions).

You do not need to answer the questions or to solve the problems. Instead, you are asked to judge the questions in terms of their clarity and relevance. The clarity refers to how easy the item is to understand. Is it likely to be ambiguous for an undergraduate in physics? Is the task(s) it refers to clear? Or should it be rephrased differently? The relevance rather pertains to how connected the item is to the cognitive ability it aims at assessing. Can you easily see the link between them? Please refer to the following scales to assess each item:

CLARITY:	(1) Not clear at all	(2) Somewhat unclear	(3) Clear	(4) Very clear
RELEVANCE:	(1) Not relevant at all	(2) Somewhat irrelevant	(3) Relevant	(4) Very relevant

There are spaces for you to make comments or suggestions.

Please feel free to use them as needed.

Template: Problem 1

Please consider the following problem statement. Then, answer the questions A to E.

Insert the Problem-1 actual statement here.

Before actually solving the problem, take the time to write down a plan of action (call it "Initial Solution Plan" in your notebook) and justify every step of your plan. In other words, say why and how each step is important for achieving the solution. Include as much details as possible. You can always revise your plan later on if you feel it needs readjustments.

Clarity: 1 2 3 4
Relev. : 1 2 3 4

Comments or suggestions as a reviewer: ____________________

____

____

____

____

Try to estimate what a realistic range of answers to this problem might be. Also, try to justify why your forecast makes sense. When you are done with solving the problem, it should help you determine if your answer makes sense. Make sure to specify the units you are using for your prediction.

Clarity: 1 2 3 4
Relev. : 1 2 3 4

Comments or suggestions as a reviewer: ____________________

____

____

____

____

APPENDIX K: PRE-TEST (PROBLEM-SOLVING EXERCISES)

Name: ________________________________ Participant #________
Date: ______________

Problem-solving in Electromagnetism

Josée Bouchard
Centre for University Teaching and Learning
McGill University

This questionnaire has been developed as part of a doctoral thesis study and is intended to gather information on higher-order thinking processes and problem-solving abilities of physics undergraduates in advanced electromagnetism courses. Your participation in completing this questionnaire is very important and will make a valuable contribution to the study. It should not take you more than 50 minutes to respond to the 2 problems.

Confidentiality of Responses

Only the researcher will have access to the problem solutions gathered from individual students. Your professor for this course of electromagnetism will not see your answers. No information that might identify you as an individual will be shared with anyone.

Instructions

- You will be provided with a notebook, please use it at all times to answer the questions. Whether you are drafting a solution, sorting out your thoughts, drawing a little graph or a schema, performing calculations, starting over if you are not satisfied with your first attempt, or writing down your final answer, please use this notebook to write down everything.

- The participant number on this questionnaire should match the one on your notebook. You need to write your name only on this questionnaire. This will help keeping your responses to this questionnaire together with responses to the survey you might have already completed.

- Calculators, textbooks and class notes are allowed.

Your answers to this questionnaire will not impact on your grade in this course and, as mentioned previously, your professor will never see them. So, just do your best!

Thank you very much for your participation to the study! It is greatly appreciated.

Best wishes for a successful semester!

Winter 2004

Pre-test / Problem-solving Page 1

Note: Problem # 1.1 and # 1.2 have the same structure and format. You need to answer either # 1.1 **or** # 1.2, not both. Please choose the one your feel the most comfortable with and answer the questions that are related to it in your notebook. In other words, if you choose to solve the problem #1.1, you do not need to solve #1.2 and vice versa. Please answer the questions related to Problem # 2. either way.

Problem # 1.1*

[* Adapted from "Advanced Physics Problems", Dr. M. Breinig, Department of Physics and Astronomy, University of Tennessee.]

Please consider the following problem statement. Then, answer the questions A to E.

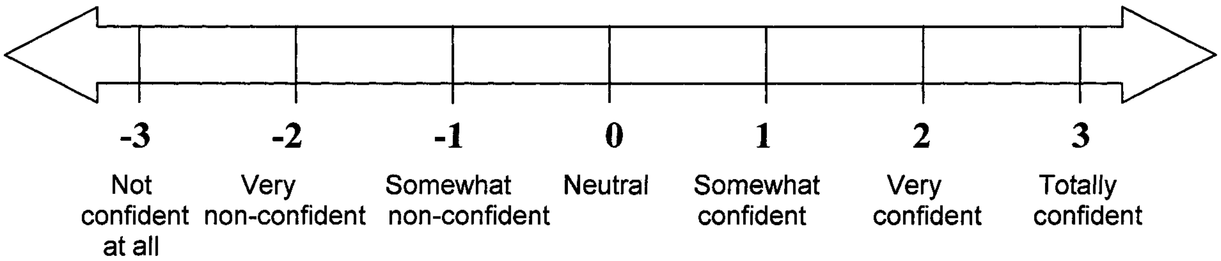
A conducting circular loop made of wire of diameter "d", resistivity "ρ", and mass density "ρ_m" is falling from a great height "h" in a magnetic field with a component $B_z = B_0(1 + kz)$, where "k" is some constant. The loop of diameter "D" is always parallel to the x-y plane. Disregard air resistance, and find the terminal velocity of the loop.

A. Before actually solving the problem, take the time to write down a plan of action (call it "Initial Solution Plan" in your notebook) and justify every step of your plan. In other words, say why and how each step is important for achieving the solution. Include as much details as possible. You can always revise your plan later on if you feel it needs readjustments.

B. Still in your notebook, try to estimate what a realistic range of answers to this problem might be. Also, try to justify why your forecast makes sense. When you are done with solving the problem, it should help you determine if your answer makes sense. Make sure to specify the units you are using for your prediction.

C. Solve the problem in your notebook. As you are solving the problem, you might realize that your initial solution plan needs a few modifications. Should it be the case, write these modifications down in your notebook but please keep your "Initial Solution Plan" intact. Additions or changes to your plan, if any, should be written down separately from your initial plan (e.g., you might call it "Revised Solution Plan" or "Adjustments to Solution Plan" for example, in your notebook).

D. Now that you have solved or have attempted to solve the problem 1.1, how confident are you about the robustness of your overall solution plan and of the exactness of your actual solution? Refer to the scale below and rank your degree of confidence for both on the next page, by drawing a circle around the appropriate number directly on this questionnaire.



About the robustness of my overall solution plan for problem 1, I am:	-3	-2	-1	0	1	2	3
About the exactness of my solution and answer to problem 1, I am:	-3	-2	-1	0	1	2	3

If you did not have a chance to completely solve the problem, how confident are you about the prediction you have made when answering the question B?

About the credibility of my estimated range of answers for problem 1, I am:	-3	-2	-1	0	1	2	3

E. Finally, categorize this problem on the basis of its deep structure and surface features. Check all the elements you think are relevant to this problem within both of the following groups.

This problem is about the following law(s), equations, or principle(s) (check as many as apply):

☐ Ampère's Law
☐ Biot-Savard's Law
☐ Charge is quantified
☐ Charge is conserved
☐ Coulomb's Law
☐ Energy is conserved
☐ Faraday's Law of Induction
☐ Gauss' Law
☐ Lenz's Law
☐ Lorentz Force
☐ Maxwell's Equations
☐ Ohm's Law
☐ Poisson's Equations
☐ Other: _______________

This problems involves the following element(s) (check as many as apply):

☐ Antennas
☐ Battery
☐ Capacitor
☐ Coaxial cable
☐ Conductor
☐ Current
☐ Current density
☐ Diamagnetism
☐ Dielectric
☐ Electric dipole
☐ Electric field
☐ Electric potential
☐ Electromagnetic radiation
☐ Electromagnetic waves
☐ Ferromagnetism
☐ Flux of the electric field
☐ Hall Effect
☐ Inductance
☐ Insulator
☐ LRC Circuit
☐ Magnetic dipole
☐ Magnetic field
☐ Magnetic flux
☐ Magnets
☐ Parallel plates
☐ Paramagnetism
☐ Point charge(s) in an electric field
☐ Potential differences
☐ Retarded Potentials
☐ Self-inductance
☐ Solenoid
☐ Waveguides
☐ Other: ____________

Problem # 1.2*

[* Adapted from "Advanced Physics Problems", Dr. M. Breinig, Department of Physics and Astronomy, University of Tennessee.]

Please consider the following problem statement. Then, answer the questions A to E.

An electron accelerator employs a time varying magnetic flux through a plane circular loop of radius $R=0.85$ m, and the electrons always move in this circular path with this radius. The magnetic field B in the loop plane

$$B_r = B_0 - Kr^2, \quad r < R; \qquad B_r = 0, \quad r > R,$$

is everywhere normal to the loop plane with "r" being the distance from the loop center.

I) Show that, at any instant, the average magnetic field in the loop B_{av}, must be related to B_R by $B_{av}= 2\ B_R$. Evaluate K.

II) B_0 increases linearly from 0 to 1.2 Tesla in 5.3 sec. Deduce the energy gain per turn for the electrons and the maximum electron energy achieved.

A. Before actually solving the problem, take the time to write down a plan of action (call it "Initial Solution Plan" in your notebook) and justify every step of your plan. In other words, say why and how each step is important for achieving the solution. Include as much details as possible. You can always revise your plan later on if you feel it needs readjustments.

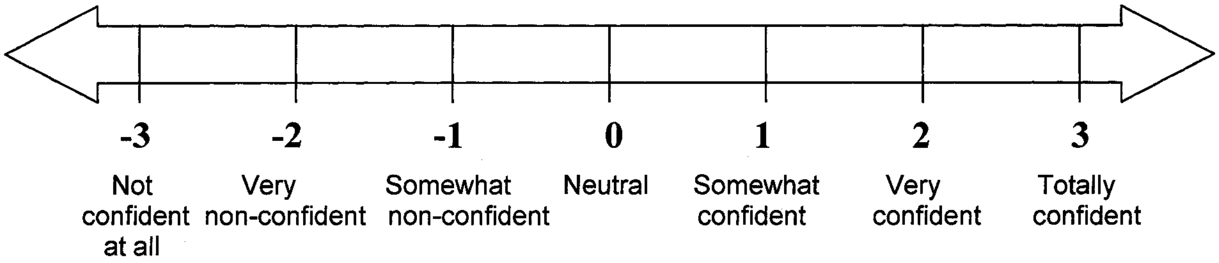
B. Still in your notebook, try to estimate what a realistic range of answers to this problem might be. Also, try to justify why your forecast makes sense. When you are done with solving the problem, it should help you determine if your answer makes sense. Make sure to specify the units you are using for your prediction.

C. Solve the problem in your notebook. As you are solving the problem, you might realize that your initial solution plan needs a few modifications. Should it be the case, write these modifications down in your notebook but keep your "Initial Solution Plan" intact. Additions or changes to your plan, if any, should be written down separately from your initial plan (e.g., you might call it "Revised Solution Plan" or "Adjustments to Solution Plan" for example, in your notebook).

D. Now that you have solved or have attempted to solve the problem 1.2, how confident are you about the robustness of your overall solution plan and of the exactness of your actual solution? Refer to the scale below and rank your degree of confidence for both on next page by drawing a circle around the appropriate number directly on this questionnaire.

Pre-test / Problem-solving

Page 4



About the robustness of my overall solution plan for problem 1, I am:	-3	-2	-1	0	1	2	3
About the exactness of my solution and answer to problem 1, I am:	-3	-2	-1	0	1	2	3

If you did not have a chance to completely solve the problem, how confident are you about the prediction you have made when answering the question B?

About the credibility of my estimated range of answers for problem 1, I am:	-3	-2	-1	0	1	2	3

E. Finally, categorize this problem on the basis of its deep structure and surface features. Check all the elements you think are relevant to this problem within both of the following groups.

<u>This problem is about the following law(s), equations, or principle(s) (check as many as apply):</u>

☐ Ampère's Law
☐ Biot-Savard's Law
☐ Charge is quantified
☐ Charge is conserved
☐ Coulomb's Law
☐ Energy is conserved
☐ Faraday's Law of Induction
☐ Gauss' Law
☐ Lenz's Law
☐ Lorentz Force
☐ Maxwell's Equations
☐ Ohm's Law
☐ Poisson's Equations
☐ Other: ______________

<u>This problems involves the following element(s) (check as many as apply):</u>

☐ Antennas
☐ Battery
☐ Capacitor
☐ Coaxial cable
☐ Conductor
☐ Current
☐ Current density
☐ Diamagnetism
☐ Dielectric
☐ Electric dipole
☐ Electric field
☐ Other: ___________
☐ Electric potential
☐ Electromagnetic radiation
☐ Electromagnetic waves
☐ Ferromagnetism
☐ Flux of the electric field
☐ Hall Effect
☐ Inductance
☐ Insulator
☐ LRC Circuit
☐ Magnetic dipole
☐ Magnetic field
☐ Magnetic flux
☐ Magnets
☐ Parallel plates
☐ Paramagnetism
☐ Point charge(s) in an electric field
☐ Potential differences
☐ Retarded Potentials
☐ Self-inductance
☐ Solenoid
☐ Waveguides

Problem 2*

[*Adapted from Redish, E. F. (2003). Teaching Physics with the Physics Suite. Hoboken, NJ: Wiley & Sons.]

For the following problem, our approach will be slightly different from the first two. We would like you to explain how you would go about solving the following problem. You are most welcome to actually solve the problem if you want to but you do not have to. However, please make sure to answer the questions A, B and C either way.

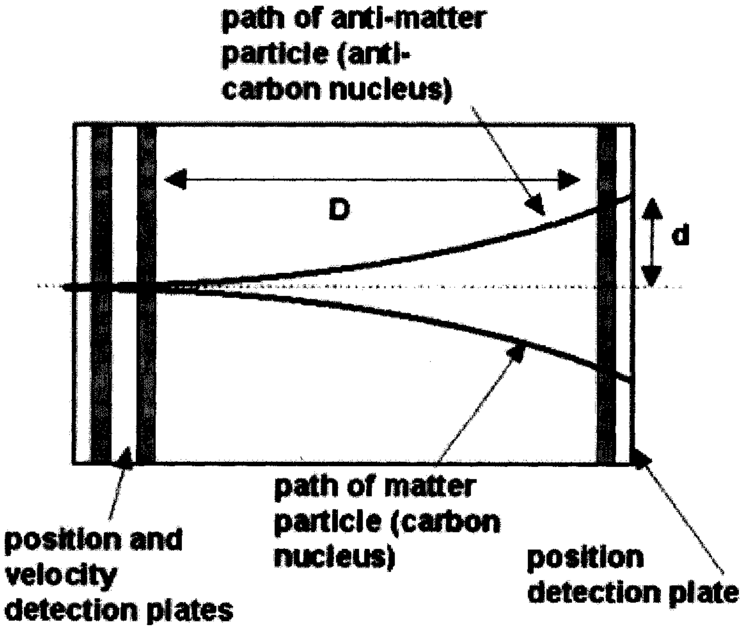
An international consortium is presently building a device to look for anti-matter nuclei in cosmic rays to help us decide if there are galaxies made of anti-matter. Anti-matter is just like ordinary matter except the basic particles (anti-protons and anti-electrons) have opposite charge from ordinary matter counterparts. (Anti-protons are negative, and anti-electrons are positive.)

A schematic of the device is shown below. A cosmic ray – say a carbon nucleus or an anti-carbon nucleus – enters the device at the left where its position and velocity are measured. It then passes through a (reasonably uniform) magnetic field. Its path is bent in one direction if its charge is positive, in the opposite direction if its charge is negative. Its deflection is measured as it goes out of the device.

I) On the figure shown below, what is the direction of the magnetic field? How do you know?

II) What is the path followed by each particle in the device? Why?

III) If you were given the magnetic field, B, the size of the device, D, the amount of charge on the incoming particle, q, and the mass of the incoming particle, M, would this be enough to calculate the displacement of the charge, d? If so, describe briefly how you would do it (but don't do it). If not, explain what additional information you would need (but don't estimate it).



A. Please explain how you would proceed to solve this problem. Elaborate on the possible trends you could take to achieve a solution. On what is based your reasoning? Include as much details as possible on the option(s) you envision in solving this problem.

B. Maybe you feel there are gaps in your knowledge, and/or missing information in the statement of the problem that prevent you from solving the problem. If so, what is it that you would need to know to actually be able to solve this problem satisfactorily?

C. Does this problem seem analogous to another situation or problem context (and perhaps more than one) that you have already encountered? Do you see any similarities between this problem and a more familiar one? Generate and explain one or many analogies you can think of for the above problem.

This is the end of the questionnaire.
Thank you very much for your valuable contribution to the study.

APPENDIX L: POST-TEST (PROBLEM-SOLVING EXERCISES)

Name : ______________________________ Participant #: _________

Problem-solving in Electromagnetism

Josée Bouchard
Centre for University Teaching and Learning
McGill University

This questionnaire has been developed as part of a doctoral thesis study and is intended to gather information on higher-order thinking processes and problem-solving abilities of physics undergraduates in advanced electromagnetism courses. Your participation in completing this questionnaire is very important and will make a valuable contribution to the study. It should not take you more than 60 minutes to respond to the 2 problems.

Confidentiality of Responses

Only the researcher will have access to the problem solutions gathered from individual students. Your professor for this course of electromagnetism will not see your answers. No information that might identify you as an individual will be shared with anyone.

Instructions

- You will be provided with a notebook, please use it at all times to answer the questions. Whether you are drafting a solution, sorting out your thoughts, drawing a little graph or a schema, performing calculations, starting over if you are not satisfied with your first attempt, or writing down your final answer, please use this notebook to write down everything.
- The participant number on this questionnaire should match the one on your notebook. You need to write your name only on this questionnaire. This will help keeping your responses to this questionnaire together with responses to the survey you might have already completed.
- Calculators, textbooks and class notes are allowed.

Your answers to this questionnaire will not impact on your grade in this course and, as mentioned previously, your professor will never see them. So, just do your best!

Thank you very much for your participation to the study! It is greatly appreciated.

Best wishes for a successful semester!

Winter 2004

Problem # 1*

[* Adapted from Fawwaz, T. U. (2001). Fundamentals of Applied Electromagnetics. Upper Saddle River, NJ: Prentice Hall.]

Please consider the following problem statement. Then, answer the questions A to E.

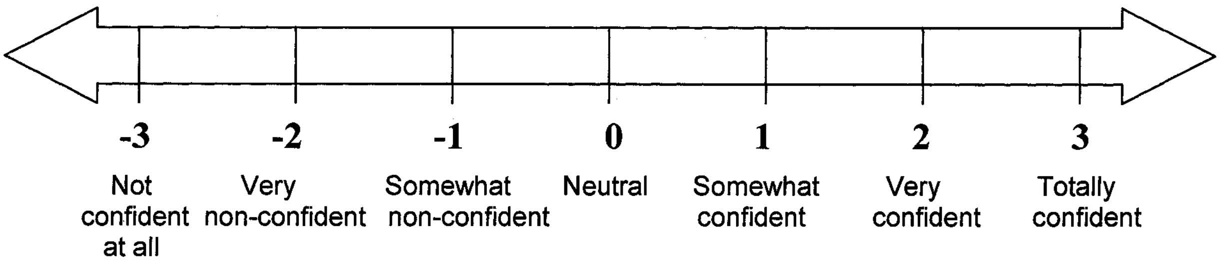
> Consider a thin film of soap in air under illumination by yellow light with λ= 0.6 μm in vacuum. If the film is treated as a planar dielectric slab with ε_r = 1.72, surrounded on both sides by air, what film thickness would produce strong reflection of the yellow light at normal incidence?

A. Before actually solving the problem, take the time to write down a plan of action (call it "Initial Solution Plan" in your notebook) and justify every step of your plan. In other words, say why and how each step is important for achieving the solution. Include as much details as possible. You can always revise your plan later on if you feel it needs readjustments.

B. Still in your notebook, try to estimate what a realistic range of answers to this problem might be. Also, try to justify why your forecast makes sense. When you are done with solving the problem, it should help you determine if your answer makes sense. Make sure to specify the units you are using for your prediction.

C. Solve the problem in your notebook. As you are solving the problem, you might realize that your initial solution plan needs a few modifications. Should it be the case, write these modifications down in your notebook but keep your "Initial Solution Plan" intact. Additions or changes to your plan, if any, should be written down separately from your initial plan (e.g., you might call it "Revised Solution Plan" or "Adjustments to Solution Plan" for example, in your notebook).

D. Now that you have solved or have attempted to solve the problem 1, how confident are you about the robustness of your overall solution plan and of the exactness of your actual solution? Refer to the scale below and rank your degree of confidence for both on next page by drawing a circle around the appropriate number directly on this questionnaire.



About the robustness of my overall solution plan for problem 1, I am:	-3	-2	-1	0	1	2	3
About the exactness of my solution and answer to problem 1, I am:	-3	-2	-1	0	1	2	3

If you did not have a chance to completely solve the problem, how confident are you about the prediction you have made when answering the question B?

About the credibility of my estimated range of answers for problem 1, I am:	-3	-2	-1	0	1	2	3

E. Finally, categorize this problem on the basis of its deep structure and surface features. Check all the elements you think are relevant to this problem within both of the following groups.

This problem is about the following law(s), equations, or principle(s) (check as many as apply):

☐ Ampère's Law
☐ Biot-Savard's Law
☐ Charge is quantified
☐ Charge is conserved
☐ Coulomb's Law
☐ Energy is conserved
☐ Faraday's Law of Induction
☐ Gauss' Law
☐ Lenz's Law
☐ Lorentz Force
☐ Maxwell's Equations
☐ Ohm's Law
☐ Poisson's Equations
☐ Other: _______________

This problems involves the following element(s) (check as many as apply):

☐ Antennas
☐ Battery
☐ Capacitor
☐ Coaxial cable
☐ Conductor
☐ Current
☐ Current density
☐ Diamagnetism
☐ Dielectric
☐ Electric dipole
☐ Electric field
☐ Other: ____________
☐ Electric potential
☐ Electromagnetic radiation
☐ Electromagnetic waves
☐ Ferromagnetism
☐ Flux of the electric field
☐ Hall Effect
☐ Inductance
☐ Insulator
☐ LRC Circuit
☐ Magnetic dipole
☐ Magnetic field
☐ Magnetic flux
☐ Magnets
☐ Parallel plates
☐ Paramagnetism
☐ Point charge(s) in an electric field
☐ Potential differences
☐ Retarded Potentials
☐ Self-inductance
☐ Solenoid
☐ Waveguides

Problem 2*

[* Adapted from Fawwaz, T. U. (2001). Fundamentals of Applied Electromagnetics. Upper Saddle River, NJ: Prentice Hall.]

For the following problem, our approach will be slightly different from the first one. We would like you to explain how you would go about solving the following problem. You are most welcome to actually solve the problem if you want to but you do not have to. However, please make sure to answer the questions A, B and C either way.

A *lossy* transmission line operating at 125 MHz has an impedance of Z_0= 40 Ω, and an attenuation constant α=2 (Np/m), and a phase constant β=0.75 rad/m. Find the line parameters *R*, *L* , *G*, and *C*.

Note: Neper (Np) is a dimensionless quantity. If α=1 Np/m, then a unit wave amplitude decreases to a magnitude e^{-1} (which is 0.3678) as it travels a distance of 1 meter. An attenuation of 1 Np/m equals 20 $\log_{10}$ e = 8.69 dB/m. The phase constant expresses the rate of change of phase that occurs with distance.

A. Please explain how you would proceed to solve this problem. Elaborate on the possible trends you could take to achieve a solution. On what is based your reasoning? Include as much details as possible on the option(s) you envision in solving this problem.

B. Maybe you feel there are gaps in your knowledge, and/or missing information in the statement of the problem that prevent you from solving the problem. If so, what is it that you would need to know to actually be able to solve this problem satisfactorily?

C. Does this problem seem analogous to another situation or problem context (and perhaps more than one) that you have already encounter? Do you see any similarities between this problem and a more familiar one? Generate and explain one or many analogies you can think of for the above problem.

This is the end of the questionnaire.
Thank you very much for your valuable contribution to the study.

APPENDIX M: PBL PROBLEM

McGill PBL

Spatial Microwave Ovens

You are a group of physicists working for a large research company. You group has been asked to submit a proposal to NASA for a contract to redesign some of the components of a microwave oven to be used in the Mars project. The microwaves will be used for various applications including heating food in the proposed Mars Space Station. In short, the project is to design and produce 1000 microwaves but your group's responsibility is solely for the design.

When using the microwave oven to heat substances as a part of an experimental protocol, the personnel in the Space Station will need to be able to monitor precisely the temperature of whatever it is they heat in the microwave oven. In doing so, they want to use an infrared thermometer to measure the temperature of the food (or whatever other substances) heated in the oven. This constraint commands that you drill a square hole in the metal shield of the oven while preserving the astronauts' security when they use the oven. In other words, how big (or how small) can the hole be while still avoiding the unwanted leakage effect or microwaves "escaping" outside of the cooking chamber and potentially harming bystanders? You want to provide a 99% shielding.

NASA also finds that the current microwave oven model is taking up too much space and they require a significant reduction in its volume. Space is an issue in space! The magnetron cannot be changed as that contract has already been awarded. The size of the cooking chamber cannot be modified either since it is already the smallest they could possibly have to fit their samples and food. You might want to redesign the waveguide though but you cannot change its length which is 30 cm. NASA can provide you with 1 millimetre-thin aluminum sheets to design a rectangular waveguide. Other substances such as air, polyethylene, polystyrene, and Teflon (PTFE) are available and allowed in space.

You will present your proposal at 1:00 p.m. on Thursday March 25th. Your presentation must not take more than 10 minutes. It will be followed by five minutes of questions.

Bouchard & PBL Tutor Winter 2004

APPENDIX N: OBSERVATION GRID

Observation Grid: Electromagnetic Waves

Date: ________________ Time: ________________
Students Attending:____________________________

Instructional Techniques[1]

Starts class w/ a Plan or Goals **Overall E&R**
Y N **1 2 3**

Uses Schemas or Graphs **Overall E&R**
☐☐☐☐☐☐☐☐☐☐☐ **1 2 3**
☐☐☐☐☐☐☐☐☐☐☐

Asks Questions **Overall E&R**
☐☐☐☐☐☐☐☐☐☐☐ **1 2 3**
☐☐☐☐☐☐☐☐☐☐☐

Student(s) ask(s) Question(s) **Overall E&R**
☐☐☐☐☐☐☐☐☐☐☐ **1 2 3**
☐☐☐☐☐☐☐☐☐☐☐

Explicit Link w/ Prior Knowl. **Overall E&R**
☐☐☐☐☐☐☐☐☐☐☐ **1 2 3**

Uses Anecdotes or Humor **Overall E&R**
☐☐☐☐☐☐☐☐☐☐☐ **1 2 3**

Uses Analogies **E&R**
☐☐☐☐☐☐☐☐☐☐☐ **1 2 3**

Provides Examples or Applic. **Overall E&R**
☐☐☐☐☐☐☐☐☐☐☐ **1 2 3**
☐☐☐☐☐☐☐☐☐☐☐

Allows enough Time to Answer Questions
☐☐☐☐☐☐☐☐☐☐☐
☐☐☐☐☐☐☐☐☐☐☐

Answers Students' Questions **Overall E&R**
☐☐☐☐☐☐☐☐☐☐☐ **1 2 3**
☐☐☐☐☐☐☐☐☐☐☐

Models Reason. or Probl.-Solv. **Overall E&R**
☐☐☐☐☐☐☐☐☐☐☐ **1 2 3**

In-class & homew Probl/Exerc. **Overall E&R**
c ☐☐☐☐☐☐☐☐☐☐☐ **1 2 3**
h ☐☐☐☐☐☐☐☐☐☐☐ **1 2 3**

Variation of stimuli
- Pace: ____
- Teaching aids & Materials: ____________________________

Management
- Class dynamics: ______________________________________
- Time: ____

Other: ____
____

---

[1] Categories and items inspired by the "*Grille d'observation sur les techniques d'enseignement*" (Cabral, Viau, Bédard, Bouchard, & Dubeau, 1997). Each occurrence (if any) is rated with a 3-point ordinal rating from low to high for adequacy (effectiveness and relevance). Then, at the end of each period of observation, another 3-point ordinal rating from low to high is used to assess the overall or average adequacy (effectiveness and relevance) of the use of the technique during the entire length of the observed class period.

Instructional Features [2]

Lesson segments:

1. Introduction **1 2 3 N/A**
2. Review **1 2 3 N/A**
3. Development **1 2 3 N/A**
4. Discussion **1 2 3 N/A**
5. Summary **1 2 3 N/A**

Content (*also see field notes for actual description*):

1. Emphasis on conceptual understanding **1 2 3 N/A**
2. Accuracy of subject matter content **1 2 3 N/A**
3. Focus on scientific conceptions **1 2 3 N/A**
4. Appropriateness of subject matter representation **1 2 3 N/A**

Teacher Role:

1. Eliciting or diagnosing misconceptions **1 2 3 N/A**
2. Presenting discrepant events to challenge student thinking **1 2 3 N/A**
3. Encouraging discussion and construction of scientific conceptions **1 2 3 N/A**

Student Role:

1. Making predictions and explanations **1 2 3 N/A**
2. Describing results or reasoning **1 2 3 N/A**
3. Applying new conceptions (in class) **1 2 3 N/A**
4. Discussing ideas with others **1 2 3 N/A**

Activities/Materials (in class):

1. Activities/Materials permit students to produce immediate, salient, and varied effects **1 2 3 N/A**
2. Activities foster the students' active participation **1 2 3 N/A**
3. Activities/Materials facilitate conceptual understanding **1 2 3 N/A**
4. Activities permit students' immediate self-assessment (understand., reasoning, results) **1 2 3 N/A**

Management:

1. Appropriate spatial arrangement **1 2 3 N/A**
2. Discussion of assignments and evaluations **1 2 3 N/A**
3. Monitoring and feedback on assignments and evaluations **1 2 3 N/A**

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[2] Categories and items adapted from Kagan's (1990) *Configuration Checklist for evaluating a teaching performance* (pertains to conceptual change teaching in science). For each instructional feature, a 3-point ordinal rating (from low to high) is used to assess implementation when applicable. The N/A category was added to accommodate for instructional features not observed at all during a specific class period.

APPENDIX O: SEMI-STRUCTURED INTERVIEW GUIDE

Semi-directed Interview Guide:

Professor & PBL Tutor

1. Since the beginning of your academic career, have you always taught physics (at what levels)?
2. How is physics different from other topics in higher education?
3. How do you define your role as a physics professor? Has it changed through the years, since you begun your career? How and why?
4. How do you define the undergraduate students' role as physics students? Again, has this role changed since the beginning of your academic career? How and why?
5. How do you go about preparing your courses?
6. What do you expect your students to achieve? What are the global learning outcomes you have for your students? Are they explicit?
7. How do you know your students learn? What do you think are the best indicators of students' learning?
8. What is/are the most challenging aspect(s) or your teaching career?
9. What is/are the most rewarding aspect(s) or your teaching career?
10. What do you think are the most desirable intellectual and cognitive abilities that physics students should ideally develop? Can you define them?
11. What about problem-solving abilities? What makes a good problem-solver in physics?
12. How do you foster the development of these higher-order thinking processes among your students?

APPENDIX P: APL/CORPS QUESTIONNAIRE CONSENT FORM

McGill

Students' Approaches to Learning
and Higher-order Thinking in Solving Physics Problems

Student Consent Form (Survey)

I agree to participate in this doctoral dissertation research conducted by Josée Bouchard under the supervision of Dr. Alenoush Saroyan of the Centre for University Teaching and Learning (CUTL) and the Department of Educational and Counselling Psychology at McGill University.

I understand that the main purpose of this investigation is to study physics undergraduate students' approaches to physics learning, higher-order thinking processes, along with problem-solving abilities when solving electromagnetism problems.

I understand that my role in the study will include completing a survey on my approaches to physics learning and perceived role as a physics student. Filling this questionnaire will take approximately 45 minutes.

I understand that my participation and the data generated in the study will be treated with confidentiality. My identity will be protected and all records will be coded to guarantee anonymity. My professor will never see my answers to any of the assessments.

I understand that the data from this study may be published.

I have voluntarily agreed to participate in this research and understand that I may withdraw at my own discretion and for any reason at any time.

Name (please print): ______________________________

Signature: ______________________________________

Date: ____

Fall 2003

APPENDIX Q: PRE-TEST CONSENT FORM

McGill *Students' Approaches to Learning*
and Higher-order Thinking in Solving Physics Problems

Student Consent Form (Pre-test)

I agree to participate in this doctoral dissertation research conducted by Josée Bouchard under the supervision of Dr. Alenoush Saroyan of the Centre for University Teaching and Learning (CUTL) and the Department of Educational and Counselling Psychology at McGill University.

I understand that the main purpose of this investigation is to study physics undergraduate students' approaches to physics learning, higher-order thinking processes, along with problem-solving abilities when solving electromagnetism problems.

I understand that my role in the study will include answering one problem-solving assessment (pre-test). Filling this questionnaire will take approximately 50 minutes.

I understand that my participation and the data generated in the study will be treated with confidentiality. My identity will be protected and all records will be coded to guarantee anonymity. My professor will never see my answers.

I understand that the data from this study may be published.

I have voluntarily agreed to participate in this research and understand that I may withdraw at my own discretion and for any reason at any time.

Name (please print): ______________________________

Signature: ______________________________

Date: ______________________________

Winter 2004

APPENDIX R: PBL WEEK SCHEDULE AND ACTIVITIES

	Monday	Tuesday	Wednesday	Thursday	Friday
DESCRIPTION OF THE ACTIVITY	Introduction to PBL & Tutorial Process (Interactive Lecture)	Students' Team meeting	Public Conference on PBL	PBL Session 2	Post-test: Problem-solving Assessment
LEADER(S)	Guest PBL Tutor	Students	Guest PBL Tutor	Guest PBL Tutor	N/A
LENGTH OF THE ACTIVITY	**1 hour**	**2 hours** (+ a coffee break)	**2 hours**	**2 hours** (+ a lunch)	**1 hour**
CATEGORY OF ACTIVITY	Mandatory	Mandatory	Recommended	Mandatory	Mandatory
DATA COLLECTED	▸ Videotape	▸ Field notes ▸ Team work on flip-chart sheets	N/A	▸ Videotape ▸ Field notes ▸ Team work on flip-chart sheets ▸ Students' notebooks w/ personal notes from self-directed study	▸ Students' notebooks (with plans & problem-solutions)
DESCRIPTION OF THE ACTIVITY	PBL Session 1				
LEADER	Guest PBL Tutor				
LENGTH OF THE ACTIVITY	**2 hours** (+ a dinner)				
CATEGORY OF ACTIVITY	Mandatory				
DATA COLLECTED	▸ Videotape ▸ Field notes ▸ Team work on flip-chart sheets				
SELF-DIRECTED STUDY	Students were required to dedicate at least **1 hour** that evening	Students were required to dedicate at least **1 hour** on their own, prior to the PBL Session 2			

APPENDIX S: POST-TEST CONSENT FORM

McGill

Students' Approaches to Learning and Higher-order Thinking in Solving Physics Problems

Student Consent Form (Post-test)

I agree to participate in this doctoral dissertation research conducted by Josée Bouchard under the supervision of Dr. Alenoush Saroyan of the Centre for University Teaching and Learning (CUTL) and the Department of Educational and Counselling Psychology at McGill University.

I understand that the main purpose of this investigation is to study physics undergraduate students' approaches to physics learning, higher-order thinking processes, along with problem-solving abilities when solving electromagnetism problems.

I understand that my role in the study will include answering one problem-solving assessment (post-test). Filling this questionnaire will take approximately 60 minutes.

I understand that my participation and the data generated in the study will be treated with confidentiality. My identity will be protected and all records will be coded to guarantee anonymity. My professor will never see my answers.

I understand that the data from this study may be published.

I have voluntarily agreed to participate in this research and understand that I may withdraw at my own discretion and for any reason at any time.

Name (please print): ______________________________

Signature: ______________________________________

Date: ____

Winter 2004

APPENDIX T: PROFESSOR CONSENT FORM

McGill

Students' Approaches to Learning
and Higher-order Thinking in Solving Physics Problems

Professor Consent Form

I agree to participate in this doctoral dissertation research conducted by Josée Bouchard under the supervision of Dr. Alenoush Saroyan of the Centre for University Teaching and Learning (CUTL) and the Department of Educational and Counselling Psychology at McGill University.

I understand that the main purpose of this investigation is to study physics undergraduate students' approaches to physics learning, higher-order thinking processes, along with problem-solving abilities when solving electromagnetism problems.

I understand that my role in the study will include: a) providing my collaboration on the validation of the data collection instruments prepared by the main researcher and b) giving access to my classroom to the main researcher at least ten (10) times during the current semester (Winter 2004) so she can document the regular instructional context in my courses of "Electromagnetic Waves".

I will also be interviewed by the principal investigator on my views on physics teaching and learning and on my perspectives of students' higher-order thinking processes and problem-solving abilities.

I understand that my participation and the data generated in the study will be treated with confidentiality. My identity will be protected and all records will be coded to guarantee anonymity.

I understand that the data from this study may be published.

I have voluntarily agreed to participate in this research and understand that I may withdraw at my own discretion and for any reason at any time.

Name (please print): ______________________________

Signature: ______________________________________

Date: ____

APPENDIX U: TUTOR CONSENT FORM

McGill *Students' Approaches to Learning and Higher-order Thinking in Solving Physics Problems*

Problem-based Learning Tutor Consent Form

I agree to participate in this doctoral dissertation research conducted by Josée Bouchard under the supervision of Dr. Alenoush Saroyan of the Centre for University Teaching and Learning (CUTL) and the Department of Educational and Counselling Psychology at McGill University.

I understand that the main purpose of this investigation is to study physics undergraduate students' approaches to physics learning, higher-order thinking processes, along with problem-solving abilities when solving electromagnetism problems.

I understand that my role in the study will include leading two problem-based learning (PBL) sessions with a small group of undergraduate students and introducing them to the PBL and Tutorial process beforehand. I will also be interviewed by the principal investigator on my views on physics teaching and learning and on my perspectives of students' higher-order thinking processes and problem-solving abilities.

I understand that my participation and the data generated in the study will be treated with confidentiality. My identity will be protected and all records will be coded to guarantee anonymity.

I understand that the data from this study may be published.

I have voluntarily agreed to participate in this research and understand that I may withdraw at my own discretion and for any reason at any time.

Name (please print): ______________________________

Signature: ______________________________________

Date: ____

APPENDIX V: RAW SCORES AND DESCRIPTIVE STATISTICS FOR LIKERT SCALE ITEMS

Item	Position in Survey	N	Min	Max	Sum	Mean	Std. Dev.
Comfort Prog 1	11	51	1	5	187	3.67	1.227
Stud. Part. 1	14	51	1	7	168	3.29	1.501
Stud. Part. 2	15	51	1	7	160	3.14	1.844
Import grades 2	19	51	1	5	203	3.98	.948
Str&Weak 1	22	51	1	5	152	2.98	1.122
Str&Weak 2	23	51	1	5	103	2.02	1.157
Import grades 1	24	50	1	5	185	3.70	1.055
Comm Self-disc 1	25	50	1	5	195	3.90	1.233
Comm Self-disc 2	26	51	1	5	209	4.10	1.136
Study homew 5	27	51	1	4	92	1.80	1.020
Prep exam 5	28	51	1	5	198	3.88	1.194
Links 2	29	47	1	5	174	3.70	1.020
Def L Phys 3	32	51	1	5	130	2.55	1.137
Def L Phys 1	33	51	1	5	156	3.06	1.103
Imp intel abilit 2	34	48	1	5	117	2.44	1.165
Def L Phys 2	35	51	1	5	161	3.16	1.362
Imp intel abilit 5	36	51	1	5	137	2.69	1.273
Imp intel abilit 4	37	51	1	5	91	1.78	1.045
Critic Think 5	38	51	1	4	101	1.98	.905
Truths Facts 2	39	51	1	5	121	2.37	1.248
Perc Imp Lives 1	40	51	1	5	200	3.92	1.163
Critic Think 4	41	51	1	5	129	2.53	1.206
Perc Imp Lives 2	42	51	1	5	137	2.69	1.086
Career Opt 3	43	49	1	5	184	3.76	1.128
Imp intel abilit 3	44	51	2	5	188	3.69	.905
Perc Imp Lives 4	45	51	1	5	116	2.27	1.234
Comfort Instr 2	49	51	1	5	117	2.29	1.082
Pers. L goals 1	50	50	1	7	260	5.20	1.370
Comfort quest 1	51	51	1	6	118	2.31	1.568
Study homew 3	52	50	1	7	251	5.02	1.708
Prep exam 3	53	51	1	7	152	2.98	1.881
Prep exam 4	54	51	1	7	212	4.16	1.678

Item	Position in Survey	N	Min	Max	Sum	Mean	Std. Dev.
Metacogn 1	55	51	1	7	228	4.47	1.782
Metacogn 2	56	51	2	7	295	5.78	1.119
Comm Self-disc 3	57	51	3	7	287	5.63	1.216
Prep exam 1	58	51	1	7	227	4.45	1.983
Critic Think 2	59	51	2	7	252	4.94	1.475
Links 1	60	51	2	7	277	5.43	1.330
Pers. L goals 2	61	50	1	7	181	3.62	1.602
Perc imp Lives 5	62	51	1	7	189	3.71	1.628
Critic Think 1	63	50	1	6	201	4.02	1.392
Metacogn 3	64	50	1	6	175	3.50	1.529
Study homew 4	65	50	1	7	143	2.86	1.525
Comfort quest 2	66	50	1	7	195	3.90	1.799
Challeng views 1	67	50	1	7	198	3.96	1.702
Comfort quest 3	68	50	1	7	252	5.04	1.807
Study homew 1	69	50	1	7	169	3.38	2.029
Critic Think 3	70	50	1	7	189	3.78	1.866
Prep exam 2	71	50	1	7	288	5.76	1.379
Metacogn 4	72	50	1	7	207	4.14	1.852
Comfort prog 2	73	50	1	4	158	3.15	.694

APPENDIX W: EIGENVALUES AND EXPLAINED VARIANCE IN THE INITIAL PRINCIPAL COMPONENTS ANALYSIS (51 ITEMS)

Component	Initial Eigenvalues		
	Total	% of Variance	Cumulative %
1	6.673	13.084	13.084
2	6.013	11.790	24.874
3	3.795	7.441	32.315
4	3.475	6.813	39.128
5	2.964	5.813	44.940
6	2.625	5.148	50.088
7	2.374	4.654	54.742
8	2.240	4.392	59.134
9	2.079	4.077	63.211
10	1.899	3.723	66.934
11	1.626	3.188	70.122
12	1.578	3.095	73.217
13	1.445	2.833	76.050
14	1.196	2.346	78.396
15	1.150	2.255	**80.651**
16	.989	1.939	82.591
17	.947	1.857	84.448
18	.917	1.798	86.246
19	.775	1.520	87.766
20	.705	1.383	89.149
21	.681	1.336	90.485
22	.610	1.196	91.681
23	.599	1.174	92.856
24	.508	.996	93.852
25	.475	.932	94.783
26	.395	.775	95.558
27	.352	.691	96.249
28	.325	.637	96.887
29	.292	.572	97.458
30	.253	.496	97.955
31	.223	.437	98.392
32	.192	.376	98.768
33	.155	.304	99.072
34	.152	.299	99.371
35	.099	.193	99.564
36	.091	.178	99.742
37	.062	.121	99.863
38	.036	.070	99.933
39	.024	.048	99.981

Component	Initial Eigenvalues		
	Total	% of Vaiance	Total
40	.010	.019	100.000
41	6.75E-016	1.32E-015	100.000
42	3.71E-016	7.27E-016	100.000
43	2.33E-016	4.57E-016	100.000
44	1.24E-016	2.43E-016	100.000
45	8.71E-017	1.71E-016	100.000
46	4.51E-018	8.83E-018	100.000
47	-6.76E-017	-1.33E-016	100.000
48	-1.13E-016	-2.21E-016	100.000
49	-2.02E-016	-3.97E-016	100.000
50	-2.73E-016	-5.34E-016	100.000
51	-5.22E-016	-1.02E-015	100.000

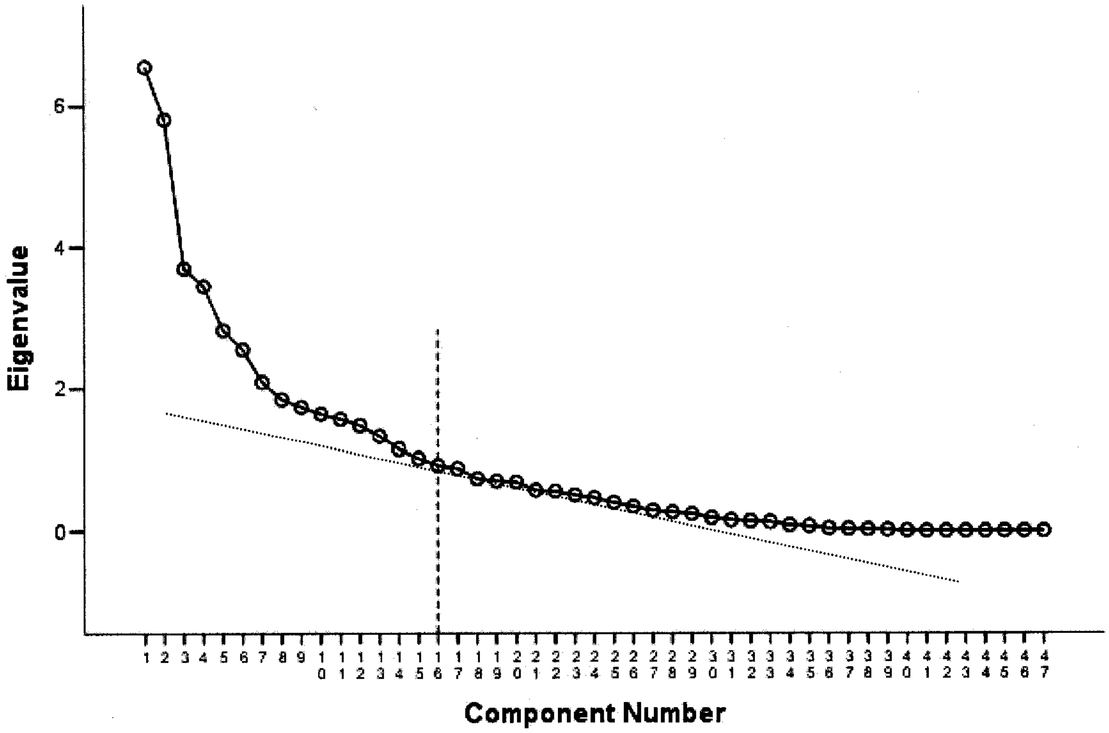
Extraction Method: Principal Components Analysis.

APPENDIX X: EIGENVALUES AND EXPLAINED VARIANCE IN THE FINAL PRINCIPAL COMPONENTS ANALYSIS (47 ITEMS)

Component	Initial Eigenvalues		
	Total	% of Variance	Cumulative %
1	6.557	13.951	13.951
2	5.811	12.363	26.314
3	3.694	7.859	34.173
4	3.440	7.320	41.493
5	2.814	5.987	47.480
6	2.541	5.405	52.885
7	2.086	4.439	57.324
8	1.841	3.918	61.242
9	1.735	3.692	64.934
10	1.638	3.484	68.419
11	1.564	3.328	71.747
12	1.476	3.140	74.886
13	1.322	2.813	77.699
14	1.146	2.437	80.137
15	1.011	2.152	**82..289**
16	.915	1.946	84.235
17	.874	1.860	86.094
18	.731	1.555	87.649
19	.698	1.485	89.134
20	.684	1.455	90.589
21	.567	1.207	91.796
22	.555	1.181	92.977
23	.500	1.064	94.041
24	.460	.978	95.019
25	.392	.834	95.854
26	.336	.715	96.569
27	.280	.596	97.165
28	.259	.550	97.715
29	.234	.499	98.214
30	.179	.381	98.595
31	.149	.318	98.913
32	.136	.288	99.202
33	.124	.263	99.465
34	.078	.166	99.631

Component	Initial Eigenvalues		
	Total	% of Variance	Cumulative %
35	.066	.140	99.771
36	.036	.076	99.848
37	.029	.062	99.909
38	.022	.048	99.957
39	.015	.033	99.989
40	.005	.011	100.000
41	5.59E-016	1.19E-015	100.000
42	1.25E-016	2.66E-016	100.000
43	5.39E-017	1.15E-016	100.000
44	-4.37E-017	-9.29E-017	100.000
45	-1.09E-016	-2.32E-016	100.000
46	-2.30E-016	-4.88E-016	100.000
47	-7.53E-016	-1.60E-015	100.000

APPENDIX Y: FINAL SOLUTION SCREE PLOT



APPENDIX Z: ROTATE COMPONENT MATRIX OF THE FINAL COMPONENT SOLUTION

	Component														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Comfort Prog 1	.825														
Pers. L goals 1	.798														
Comfort prog 2	.772							.309							
Rev. Metacogn 3	.704	-.310					-.308								
Career Opt 3	.593						.327					.373			
Study homew 3	.492	.358	.377							.354					
Rev. Lives 4	.468										.412			.361	
Prep exam 5		.834													
Prep exam 2		.820													
Prep exam 1		.717													
Def L Phys 3		.609			.483										
Critic Think 3		.521						-.462							
Rev. Prep exam 3			.713												
Study homew 4			.695												
Stud. Part. 1			.684						-.367						
Stud. Part. 2			.657	.342					-.444						
Metacogn 4			.613												
Comfort Instr 2			.488		.487									-.345	
Links 1				.823											
Critic Think 2				.734											
Import grades 2					.805	.324									
Comfort quest 2					.643							.313			
TruthFact 2		.312			.563								.327		
Import grades 1						.832									
Comm Self-disc 1		.326		-.302		.679									
Comm Self-disc 2		.384				.638									

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Comm Self-disc 3							.788								
Challeng views 1	.358			.454			.543				-.303				
Rev. Links 2				.463		.306	.536								
Rev. Imp intel abilit 2								.729							
Rev. Critic Think 5				-.321				.689							
Rev. Strength Weak 1	.395					-.385		.522				-.317			
Metacogn 2									.898						
Rev. Imp intel abilit 4					-.326				.684	.319					
Metacogn 1										.820					
Rev. Comfort quest 1			.342							.497			.364		
Pers. L goals 2	.374	-.420								.482					
Rev. Def L Phys 2											.861				
Imp intel abilit 3				.472			.480				.487				
Perc Imp Lives 1												.744			
Rev. Strenth Weak 2					-.318								.801		
Critic Think 1				.460									.562		
Perc Imp Lives 2														.890	
Critic Think 4	.324										.429			.560	
Def L Phys 1															.827
Imp intel abilit 5							.307				.322				.626
Rev. Comfort quest 3												.511			.550

Extraction Method: Principal Components Analysis.
Rotation Method: Varimax with Kaiser Normalization.

a Rotation converged in 28 iterations.

APPENDIX AA: INITIAL SCALE INTERPRETATIONS

Emerging Dimension	*A Priori* Category	Item code	Item Position in Survey	Loading	Question
Items Deleted Following the Initial Principal Component Analysis	Study & Homework	2B1	**69**		When I study for my physics courses this year, I make charts, diagrams, or tables to help me organize or summarize the course material.
	Study & Homework	2B5	**27**		In physics, I review my notes before the next class.
	Prep. for Exams	2C4	**54**		When studying for an exam in physics, I often explain the material to a friend or classmate.
	Physics in their Lives	3E5	**62**		I rarely see any relationships between material covered in my physics courses this year and other aspects of my life.
<u>Scale 1</u>: Comfort in Program – A Sense of Belonging, Being in the Right Place, Doing the Right Thing	Comfort in Program	1A1	**11**	0.825	How certain are you that your current choice of program of study is the best one for you?
	Personal Learn. Goals	2A1	**50**	0.798	In physics this year, I prefer course work that is challenging so I can learn new things.
	Comfort in Program	1A2	**73**	0.772	Which of the following best describes how you feel about your current program of study?
	Metacog. Skills	2E3	**64**	0.704	I often find that I have been reading for class in physics this year but don't know what it was all about.
	Career & Prof. Options	3H3	**43**	0.593	A good understanding of physics is necessary for me to achieve my career goals. Good grades in my physics courses this year are not enough.
	Study & Homework	2B3	**52**	0.492	I make sure that I keep up with the physics weekly readings and assignments this year.
	Physics in their Lives	3E4	**45**	0.468	Physical laws have little relation to what I experience in the real world.
<u>Scale 2</u>: Strategic & Intentional Preparation for Exam and Problem-solving Assignments	Prep. for Exams	2C5	**28**	0.834	When preparing for a physics exam, I try to anticipate the questions that I think might be included and study them.
	Prep. for Exams	2C2	**71**	0.820	When studying for an exam in physics, I practice solving problems similar to what I expect to get in the test.
	Prep. for Exams	2C1	**58**	0.717	When studying for an exam in physics, I memorize formulas and equations.
	Def. of Physics Learning	3D3	**32**	0.609	The most crucial thing in solving a physics problem is finding the right equation to use.
	Critical Thinking	2F3	**70**	0.521	When confronted with difficult material or problems in physics this year, I try to think up possible solutions and then systematically check them out.

Emerging Dimension	*A Priori* Category	Item code	Item Position in Survey	Loading	Question
Scale 3: Staying "up-to-date" Strategies	Prep. for Exams	2C3	**53**	0.713	I rarely find time to review my notes or readings in physics before an exam this year.
	Study & Homework	2B4	**65**	0.695	I work on practice exercises and end of chapter problems even if they are not required.
	Student Participation	4A1	**14**	0.684	How would you rate the degree of the students' participation in your physics classes this year? If you think that most students are active participants, choose 7, if most students almost never participate, choose 1. If the students' participation is somewhere in between, find the number that best describes the situation.
	Student Participation	4A2	**15**	0.657	Using a similar scale, how would you rate your own participation in your physics classes this year?
	Metacog. Skills	2E4	**72**	0.613	If I get confused taking notes in physics lectures this year, I make sure to sort it out after class.
	Comfort w/ Instructor	1C2	**49**	0.488	How many times did you go to your professor(s) for help with your physics course work this year.
Scale 4: Constructing Personal Meaning	Links Between Courses	2G1	**60**	0.823	I try to relate concepts and material learned in one physics course this year to those in other courses of my program, whenever possible.
	Critical Thinking	2F2	**59**	0.734	I try to develop my own understanding of physics topics, rather than only rely on the instructors' ideas.
Scale 5: Eagerness to Get the Best Out of the Class	Importance of Grades	2H2	**19**	0.805	How important is it for you to get high grades this year?
	Comfort Asking Questions	4C2	**66**	0.643	I ask the professor to clarify physics concepts if I don't understand well.
	Conceptions of Truths & Facts	3B2	**39**	0.563	In physics this year, I do not expect to understand equations in an intuitive sense; most must simply be taken as given.
Scale 6: Commit. & Self discipl.	Importance of Grades	2H1	**24**	0.832	I work very hard to get good grades in physics this year.
	Commitment & Self-Discipline	1E1	**25**	0.679	Even when I am tired, I try to complete my assignments in physics this year.
	Commitment & Self-Discipline	1E2	**26**	0.638	I set high standards for myself in my physics classes this year.

Emerging Dimension	*A Priori* Category	Item code	Item Position in Survey	Loading	Question
Scale 7: Confidence in one's Judgement and Understading	Commitment & Self-Discipline	1E3	**57**	0.788	When course work is difficult in physics, I either give up or only study the easy parts.
	Willingn. to Challenge Acc. Views	3G1	**67**	0.543	I often find myself questioning things I hear or read this year in physics to decide if I find them convincing.
	Links Between Courses	2G2	**29**	0.536	In physics, I try to see the relationships between what I'm studying and what I already know
Scale 8: Efficiency in Dealing w/ Challenges	Cogn. Abilit. Perceived as Important	3C2	**34**	0.729	A significant problem this year in physics is being able to memorize all the information I need to know.
	Critical Thinking	2F5	**38**	0.689	In doing a physics problem, if my calculation gives a result that differs significantly from what I expect, I'd have to trust the calculation.
	Percep. of Strengths & Weakn.	1D1	**22**	0.522	I find it difficult to complete my assignments in physics this year.
Scale 9: Meaning of Understand.	Metacog. Skills	2E2	**56**	0.898	When I am studying for my physics courses this year, I try to determine which concepts I don't understand well.
	Cogn. Abilit. Perceived as Important	3C4	**37**	0.684	"Understanding" physics basically means being able to recall something you've read or been shown.
Scale 10: Setting personal goals	Metacog. Skills	2E1	**55**	0.820	When I study physics, I set goals for myself in order to direct my activities and make the best out of each study period
	Comfort Asking Questions	4C1	**51**	0.497	I believe that people would think less of me if I got help in order to succeed in my physics courses this year
	Personal Learn. Goals	2A2	**61**	0.482	In physics this year, I prefer easy and familiar course material so I can get good grades.
Scale 11: Perseverance & Time Investment	Personal Def. of Physics Studying/ Learning	3D2	**35**	0.861	The best way for me to learn physics is by solving many problems rather than by carefully analyzing a few in details.
	Cogn. Abilit. Perceived as Important	3C3	**44**	0.487	Learning physics requires that I substantially rethink, restructure, and reorganize the information that I am given in class and/or in the textbook.

Emerging Dimension	*A Priori* Category	Item code	Item Position in Survey	Loading	Question
Scale 12: Impact of physics in one's life	Physics in their Lives	3E1	**40**	0.744	Learning physics made me change some of my ideas about how the physical world works.
Scale 13: Systematized and Structured Approach	Percep. of Strengths & Weakn.	1D2	▨ **23**	0.801	I have problems with taking organized class notes in physics
	Critical Thinking	2F1	**63**	0.562	When a theory, interpretation, or conclusion is presented in class or readings in physics this year, I try to decide if there is good supporting evidence.
Scale 14: Having a Personal Input	Physics in their Lives	3E2	**42**	0.890	To understand physics, I sometimes think about my personal experiences and relate them to the topic being analyzed.
	Critical Thinking	2F4	**41**	0.560	If I don't remember a particular equation needed for a problem in a physics exam there's nothing much I can do (legally!) to come up with it.
Scale 15: Having a 'Physics is Within my Reach' Attitude	Def. of Physics Learning	3D1	**33**	0.827	When learning physics, a student cannot fully understand new material unless she/he relates it to something she/he already knows.
	Cogn. Abilit. Perceived as Important	3C5	▨ **36**	0.626	Only very few specially qualified people are capable of really understanding physics.
	Comfort Asking Questions	4C3	**68**	0.550	When I can't understand the material in my physics courses this year, I ask another student for help.

▨ These items have been recoded because of their negative phrasing or connotation. Recoding prevented any confusion when the items were susequently combined into scales. Scales group items that measure a common concept and it was important to allign all items in the same direction.

APPENDIX BB: A PRIORI DIMENSIONS AND CATEGORIES OF THE SURVEY

A Priori Dimension	*A Priori* Category	Item code	Type	Item Position in Survey	Question
Personal Experience	Comfort in Program	1A1	L5	**11**	How certain are you that your current choice of program of study is the best one for you?
		1A2	L4	**73**	Which of the following best describes how you feel about your current program of study?
	Comfort w/ Instructor	1C2	L7	**49**	How many times did you go to your professor(s) for help with your physics course work this year.
	Percep. of Strengths & Weakn.	1D1	L5	**22**	I find it difficult to complete my assignments in physics this year.
		1D2	L5	**23**	I have problems with taking organized class notes in physics
		1D4	SA	**13**	As an undergraduate student in physics, what do you think your strengths and weaknesses to be? Write down three (3) of each.
	Commitment & Self-Discipline	1E1	L5	**25**	Even when I am tired, I try to complete my assignments in physics this year.
		1E2	L5	**26**	I set high standards for myself in my physics classes this year.
		1E3	L7	**57**	When course work is difficult in physics, I either give up or only study the easy parts.
Academic Experience	Personal Learn. Goals	2A1	L7	**50**	In physics this year, I prefer course work that is challenging so I can learn new things.
		2A2	L7	**61**	In physics this year, I prefer easy and familiar course material so I can get good grades.
		2A4	R	**21**	By indicating numbers from 1 to 5 in the parentheses, rank the following skills in order of importance (1 being the most important for you, 2 the second, etc.).
	Study & Homework Habits	2B1	L7	**69**	When I study for my physics courses this year, I make charts, diagrams, or tables to help me organize or summarize the course material.
		2B3	L7	**52**	I make sure that I keep up with the physics weekly readings and assignments this year.
		2B4	L7	**65**	I work on practice exercises and end of chapter problems even if they are not required.
		2B5	L5	**27**	In physics, I review my notes before the next class.
	Prep. for Exams & Evaluations	2C1	L7	**58**	When studying for an exam in physics, I memorize formulas and equations.
		2C2	L7	**71**	When studying for an exam in physics, I practice solving problems similar to what I expect to get in the test.
		2C3	L7	**53**	I rarely find time to review my notes or readings in physics before an exam this year.
		2C4	L7	**54**	When studying for an exam in physics, I often explain the material to a friend or classmate.
		2C5	L5	**28**	When preparing for a physics exam, I try to anticipate the questions that I think might be included and study them.
	Metacog. Skills	2E1	L7	**55**	When I study physics, I set goals for myself in order to direct my activities and make the best out of each study period
		2E2	L7	**56**	When I am studying for my physics courses this year, I try to determine which concepts I don't understand well.
		2E3	L7	**64**	I often find that I have been reading for class in physics this year but don't know what it was all about.
		2E4	L7	**72**	If I get confused taking notes in physics lectures this year, I make sure to sort it out after class.

A Priori Dimension	*A Priori* Category	Item code	Type	Item Position in Survey	Question
Academic Experience (cont'd)	Critical Thinking	2F1	L7	**63**	When a theory, interpretation, or conclusion is presented in class or readings in physics this year, I try to decide if there is good supporting evidence.
		2F2	L7	**59**	I try to develop my own understanding of physics topics, rather than only rely on the instructors' ideas.
		2F3	L7	**70**	When confronted with difficult material or problems in physics this year, I try to think up possible solutions and then systematically check them out.
		2F4	L5	**41**	If I don't remember a particular equation needed for a problem in a physics exam there's nothing much I can do (legally!) to come up with it.
		2F5	L5	**38**	In doing a physics problem, if my calculation gives a result that differs significantly from what I expect, I'd have to trust the calculation.
	Perceived Links Between Courses	2G1	L7	**60**	I try to relate concepts and material learned in one physics course this year to those in other courses of my program, whenever possible.
		2G2	L5	**29**	In physics, I try to see the relationships between what I'm studying and what I already know
	Importance of Grades	2H1	L5	**24**	I work very hard to get good grades in physics this year.
		2H2	L5	**19**	How important is it for you to get high grades this year?
	Lessons Learned	2I1	O	**20**	What are some of the lessons learned from your previous year(s) in your current program? Describe two (2) lessons you derived from your academic experience in your current program. Then for each lesson, say what you do or think of differently now, if anything, as a result.
Perspective on Physics Learning	Conceptions of Truths & Facts	3B2	L5	**39**	In physics this year, I do not expect to understand equations in an intuitive sense; most must simply be taken as given.
		3B3	MD	**31**	Mini-debate on truths and facts in science.
	Cogn. & Intellectual Abilities Perceived as Important	3C2	L5	**34**	A significant problem this year in physics is being able to memorize all the information I need to know.
		3C3	L5	**44**	Learning physics requires that I substantially rethink, restructure, and reorganize the information that I am given in class and/or in the textbook.
		3C4	L5	**37**	"Understanding" physics basically means being able to recall something you've read or been shown.
		3C5	L5	**36**	Only very few specially qualified people are capable of really understanding physics.
	Personal Def. of Physics Studying/ Learning	3D1	L5	**33**	When learning physics, a student cannot fully understand new material unless she/he relates it to something she/he already knows.
		3D2	L5	**35**	The best way for me to learn physics is by solving many problems rather than by carefully analyzing a few in details.
		3D3	L5	**32**	The most crucial thing in solving a physics problem is finding the right equation to use.
		3D4	MC	**17**	Which of the following statements best fits your view? To be successful in physics...

***A Priori* Dimension**	***A Priori* Category**	**Item code**	**Type**	**Item Position in Survey**	**Question**
Perspective on Physics Learning (cont'd)	Perceived Importance of Learning Physics in their Lives	3E1	L5	**40**	Learning physics made me change some of my ideas about how the physical world works.
		3E2	L5	**42**	To understand physics, I sometimes think about my personal experiences and relate them to the topic being analyzed.
		3E4	L5	**45**	Physical laws have little relation to what I experience in the real world.
		3E5	L5	**62**	I rarely see any relationships between material covered in my physics courses this year and other aspects of my life.
	Perceived Contribution of Research to Field	3F1	MC	**46**	Scientists are having trouble predicting and explaining the behaviour of thunder storms. This could be because thunder storms behave according to a very complicated or hard-to-apply set of rules. Or, that could be because thunder storms don't behave consistently according to any set if rules, no matter how complicated and complete that set of rules is. In general, why do scientists sometimes have trouble explaining things? Please read all options before choosing one.
		3F2	MD	**30**	Mini-debate on what physics can or cannot explain.
	Willingn. to Challenge Acc. Views	3G1	L7	**67**	I often find myself questioning things I hear or read this year in physics to decide if I find them convincing.
	Career and Professional Options Envisioned	3H1	SA	**47**	Are you considering graduate studies at this point in your current program? If so, in what domain?
		3H2	O	**48**	What kind of career and professional options do you envision for yourself?
		3H3	L5	**43**	A good understanding of physics is necessary for me to achieve my career goals. Good grades in my physics courses this year are not enough.
Role & Participation in Classroom	Student Participation	4A1	L7	**14**	How would you rate the degree of the students' participation in your physics classes this year? If you think that most students are active participants, choose 7, if most students almost never participate, choose 1. If the students' participation is somewhere in between, find the number that best describes the situation.
		4A2	L7	**15**	Using a similar scale, how would you rate your own participation in your physics classes this year?
	Perceived Expect.	4B1	O	**16**	What kind of students' participation do you think your professors expect from you in the classroom? Explain.
	Comfort Asking Questions	4C1	L7	**51**	I believe that people would think less of me if I got help in order to succeed in my physics courses this year
		4C2	L7	**66**	I ask the professor to clarify physics concepts if I don't understand well.
		4C3	L7	**68**	When I can't understand the material in my physics courses this year, I ask another student for help.
	Pref. Mode of Learning	4D1	SA	**12**	Which contexts do you prefer to learn physics? Choose two of the following and then say why on the next page.
	Interest in Small-group Learn. Act.	4E1	O	**18**	How does working in a group or a team helps you (or not) to learn physics? When answering, you might want to think of laboratories, assignments, small-group activities, etc.

Legend: Lx –> x-point Likert Scale, SA –> Short Answer, R –> Ranking, MC –> Multiple Choice, MD –> Mini-debate, O –> Open Item

APPENDIX CC: CRITERIA FOR THE ASSESSMENT OF A PLAN

Problem Plan of Action Assessed on a Scale of One to Four

Score **Criteria**

4:

- all steps are logic and correct
- reasoning is clear and articulate
- appropriate use of concepts and relationships
- plan will safely lead to a complete and robust solution when applied

3:

- minor flaws in reasoning or secondary steps missing
- minor errors in concepts and/or relationships to be used
- the plan is generally good but incomplete
- almost there

2:

- serious misunderstandings
- many steps or some significant one are missing or lacking logic
- only a few elements, steps, concepts and/or relationships to be used are right

OR

- the plan is somewhat good but completely general and not at all specific to the problem at hand

Note: When asked to produce a detailed plan of action for a specific problem, some students described a very general approach to solving problems without really addressing the problem at hand or showing evidence that they had a tailored or appropriate strategy in mind. Writing a plan of action before attempting to solve a problem was an unfamiliar and complex task that some students dealt with by limiting their plans to very general and "safe" statements.

1:

- very little is right, almost no step is appropriate
- most important concepts and relationships are absent or incorrectly used
- there is no chance to achieve a robust solution with this plan

OR

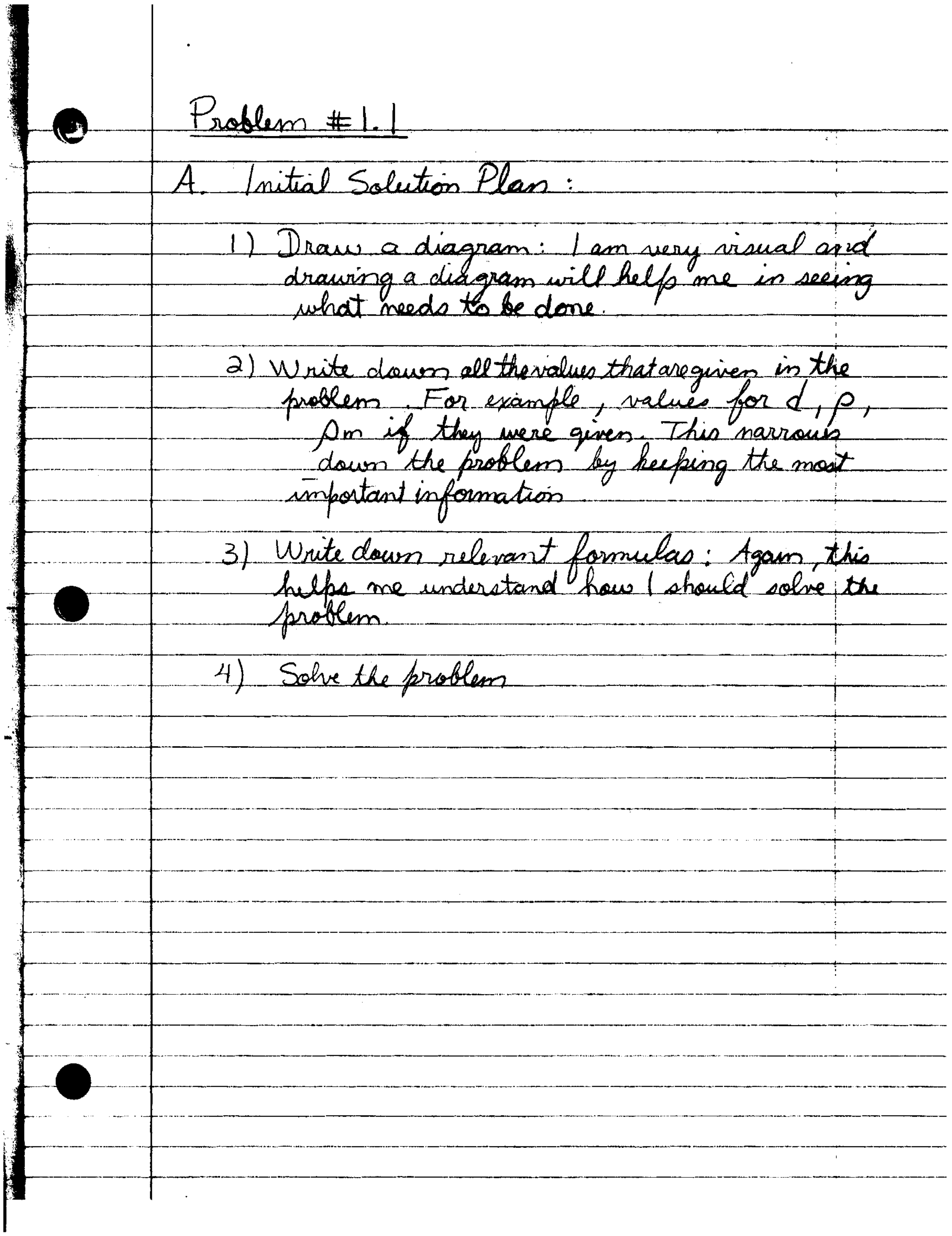
- the plan is not only unspecific to the problem at hand but weak even from a more general problem-solving perspective.

APPENDIX DD: METACOGNITIVE SKILLS INDICATORS, VARIABLES, AND CODING

Metacognitive Skills

Indicator	Variable	Description	Values	Problem Portion
Planning skills and justification	M_plan	Presence of a plan of action to solve the problem	0,1	1A
	M_plan_Q	Quality of the laid out plan	1,2,3, or 4	1A
	M_just	Presence of justification(s) for the steps of the plan	0,1	1A
	M_just_Q	Quality of justification(s) of the steps of the plan	1,2,3, or 4	1A
	M_pljt_Q	Overall Planning & Justification Score	Calculation /8	
Application of the plan and readjustments if necessary	M_appl	Presence of the actual application of the plan when solving the problem	0,1	1C
	M_appl_Q	Quality of the application of the plan towards a solution	1,2,3, or 4	1C
	M_modi	Presence of readjustments or modifications to the initial plan if necessary or evidence of monitoring	0,1	1C
	M_modi_Q	Quality of the readjustments or modifications to the initial plan or articulation of the monitoring strategies	1,2,3, or 4	1C
	M_modirp_Q	Overall Application & Readjustment Score	Calculation /8	
Accuracy of the level of confidence in the robustness of plan and exactness of solution	M_acc_pl	Accuracy of student's level of confidence about the robustness of solution plan	-3 to 3	1D
	M_acc_sl	Accuracy of student's level of confidence about the exactness of solution & answer to problem	-3 to 3	1D
	M_acc_ps	Overall accuracy of student's level of confidence about plan & solution Score	Calculation /8	
Metacognition		**Overall Index of Metacog**	**Calculation and Standardization /100**	

APPENDIX EE: EXAMPLE OF A GENERAL AND INCOMPLETE PLAN



Problem #1.1

A. Initial Solution Plan:

1) Draw a diagram: I am very visual and drawing a diagram will help me in seeing what needs to be done.

2) Write down all the values that are given in the problem. For example, values for d, ρ, ρm if they were given. This narrows down the problem by keeping the most important information

3) Write down relevant formulas: Again, this helps me understand how I should solve the problem.

4) Solve the problem

APPENDIX FF: EXAMPLE OF A DETAILED PLAN AND SOLUTION

(page 1/3)

A. Initial Solution Plan

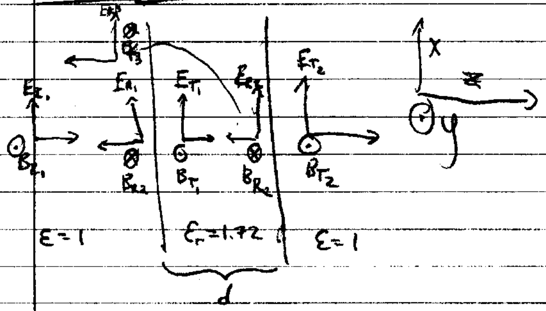
- I will begin by writing down the equations of incident, reflective and transmitted waves for E-field and B-field.
- Then I will see what components of the equation for the reflected wave will allow for the maximum value.
- Next I will isolate the term that has its dependence on film thickness, then solve for the thickness.
- I must keep in mind that there are two different transitions I need to take into consideration:

1) transmission from air to dielectric
2) " " dielectric back into air.

B

my guess is that the answer will be on the scale of only a few nm, since this is the wavelength of the incident light. More specifically, approximately $\lambda/2$.

C - Solution



(page 2/3)

$$E_{I_1} = E_{0I} \exp(j(\omega t - k_1 z))\ \hat{x}$$

$$B_{I_1} = B_{0I} \exp(j(\omega t - k_1 z))\ \hat{y}$$

$$E_{R_1} = E_{0R} \exp(j(\omega t + k_1 z))\ \hat{x}$$

$$B_{R_1} = -B_{0R} \exp(j(\omega t + k_1 z))\ \hat{y}$$

$$E_{T_1} = E_{0T} \exp(j(\omega t - k_2 z))\ \hat{x}$$

$$B_{T_1} = B_{0T} \exp(j(\omega t - k_2 z))\ \hat{y}$$

$$k_1 = \omega\sqrt{\varepsilon_0 \mu_0}$$

$$k_2 = \omega\sqrt{\varepsilon\varepsilon_0 \cancel{\mu}\mu_0}$$

take $\mu = 1$

$$E_{R_{tot.}} = E_{R_1} + E_{T_3} = E_{R_1} + (E_{T_2} - E_{T_1})$$

$$= \Big[\underbrace{E_{0R} \exp(j(\omega t + k_1 z))}_{z=0}\Big] + \Big[\underbrace{E_{0T_3} \exp(j(\omega t - k_1 z))}_{z=d} - \underbrace{E_{0T} \exp(j(\omega t - k_2 z))}_{z=0}\Big]$$

now,

$$f = \frac{c}{\lambda} = \frac{3 \cdot 10^8}{0.6 \cdot 10^{-9}} = 5 \cdot 10^{17}\ Hz$$

$$\omega = 2\pi f = 3.14 \times 10^{18}$$

so, at the interface we let $z=0$ for simplicity.

⟹ "Revised Plan Solution"

plot

$$\Big[(\omega t + k_1 \overset{z=0}{z}) + (\omega t - k_1 \overset{z=d}{z})\Big] \text{ Vs. } z$$

to find where the maximum is. The maximum here will also create a max. value for E_{Rtot}.

So, the max. of this graph will be our solution.

(unfortunately, I do not have a computer to plot:

$2\omega t - k_1 z$ vs. z

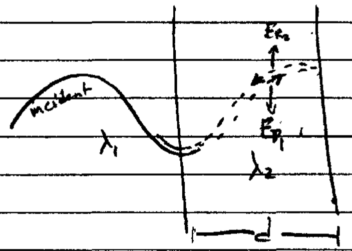
although looking at it now, it appears to be a

(page 3/3)

linear function, which means I have done something wrong.)

2nd Revised Plan Solution

-calculate the size of wavelength within the dielectric. the best reflection will come about when $\lambda_2/2$ is the distance, because of the drawing below.



$F \lambda_2 = \frac{\lambda_1}{n}$

$\lambda_2 = 0.349 \mu m$

so, $\frac{\lambda_2}{2} = \frac{0.349 \mu m}{2} = d$

thus,

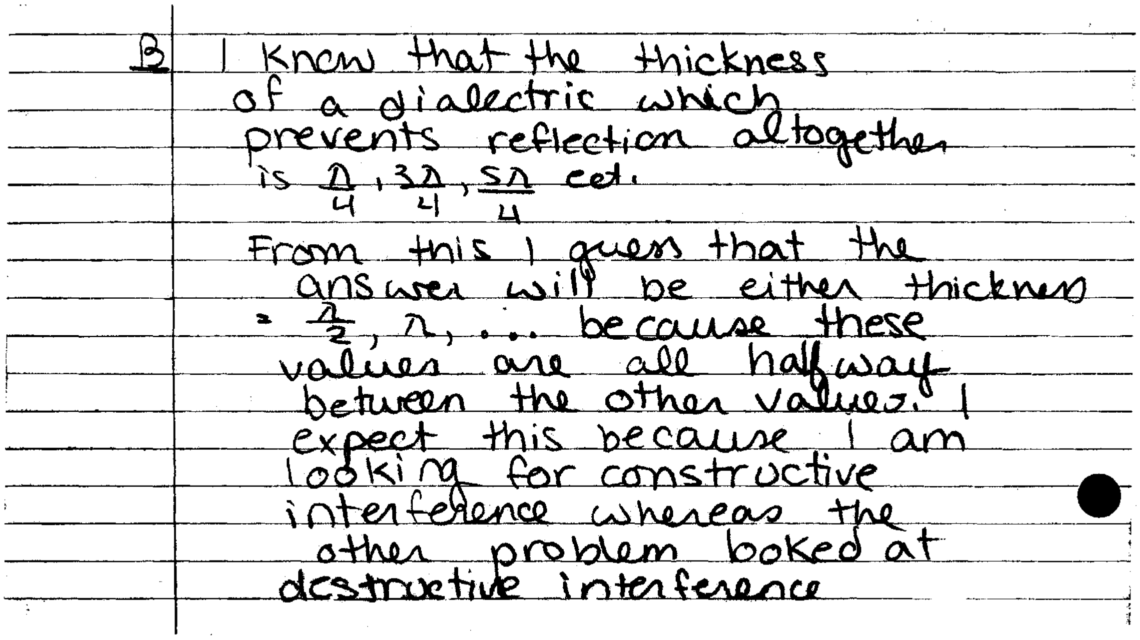
$\boxed{d = 0.1745 \mu m}$

APPENDIX GG: CRITICAL THINKING INDICATORS, VARIABLES, AND CODING

Critical Thinking

Indicator	Variable	Description	Values	Problem
Discriminating ability	CT_discr	Evidence of discrimination between relevant & irrelevant data in problem	1,2,3, or 4	1C
Ability to categorize the problem on the basis of surface & deep structures	CT_surf	Ability to categorize the problem on the basis of *surface* structures	1,2,3, or 4	1E
	CT_deep	Ability to categorize the problem on the basis of *deep* structures	1,2,3, or 4	1E
	CT_sfdp	Overall Ability to categorize the problem on the basis of surface & deep structures Score	Calculation /8	
Ability to estimate a realistic range of answers	CT_est	Presence of an estimated range of answers	0,1	1B
	CT_est_Q	Quality (realism) of estimated range of answers	1,2,3, or 4	1B
	CT_just	Presence of justification(s) for the estimated range of answers	0,1	1B
	CT_just_Q	Quality of the justification(s) for the estimated range of answers	1,2,3, or 4	1B
	CT_esjt	Overall ability to estimate a realistic range of answers Score	Calculation /8	
Critical Thinking		**Overall Index of Critical Thinking**	**Calculation and Standardization /100**	

APPENDIX HH: EXAMPLE OF A REALISTIC RANGE OF ANSWERS ESTIMATE



B

I know that the thickness of a dialectric which prevents reflection altogether is $\frac{\lambda}{4}, \frac{3\lambda}{4}, \frac{5\lambda}{4}$ ect.

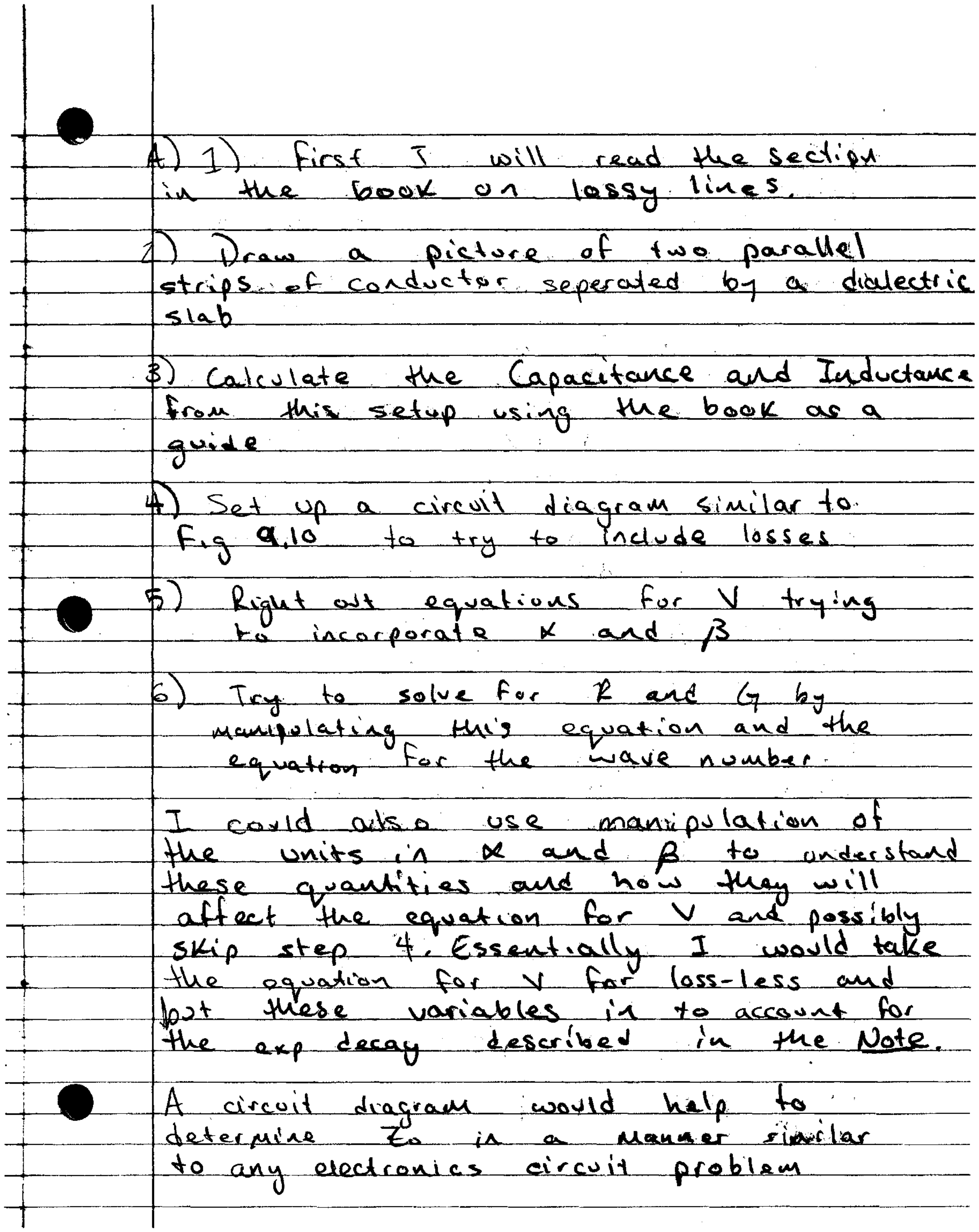
From this I guess that the answer will be either thickness = $\frac{\lambda}{2}, \lambda, \ldots$ because these values are all halfway between the other values. I expect this because I am looking for constructive interference whereas the other problem looked at destructive interference

APPENDIX II: PHYSICAL INTUITION INDICATORS, VARIABLES, AND CODING

Physical Intuition

Indicator	Variable	Description	Values	Problem
Ability to anticipate trends or alternatives	PI_alt	Presence of possible trends or alternatives to achieve a solution	0,1	2A
	PI_alt_Q	Quality (level of articulation and reasoning) of the trends to achieve a solution	1,2,3, or 4	2A
Ability to clearly identify gap(s) in knowledge or missing info in the problem	PI_gap	Presence of identified gap(s) in knowledge or missing info in problem statement	0,1	2B
	PI_gap_Q	Quality (clarity and articulation) of identified gap(s) in knowledge or missing info in problem statement	1,2,3, or 4	2B
Ability to generate analogies	PI_ana	Presence of analogous situation(s)	0,1	2C
	PI_ana_Q	Quality of description and explanation of analogous situation(s)	1,2,3, or 4	2C

APPENDIX JJ: EXAMPLE OF EXCELLENT TRENDS TO TACKLE AN UNFAMILIAR PROBLEM



A) 1) First I will read the section in the book on lossy lines.

2) Draw a picture of two parallel strips of conductor seperated by a dialectric slab

3) Calculate the Capacitance and Inductance from this setup using the book as a guide

4) Set up a circuit diagram similar to Fig 9.10 to try to include losses

5) Right out equations for V trying to incorporate α and β

6) Try to solve for R and G by manipulating this equation and the equation for the wave number.

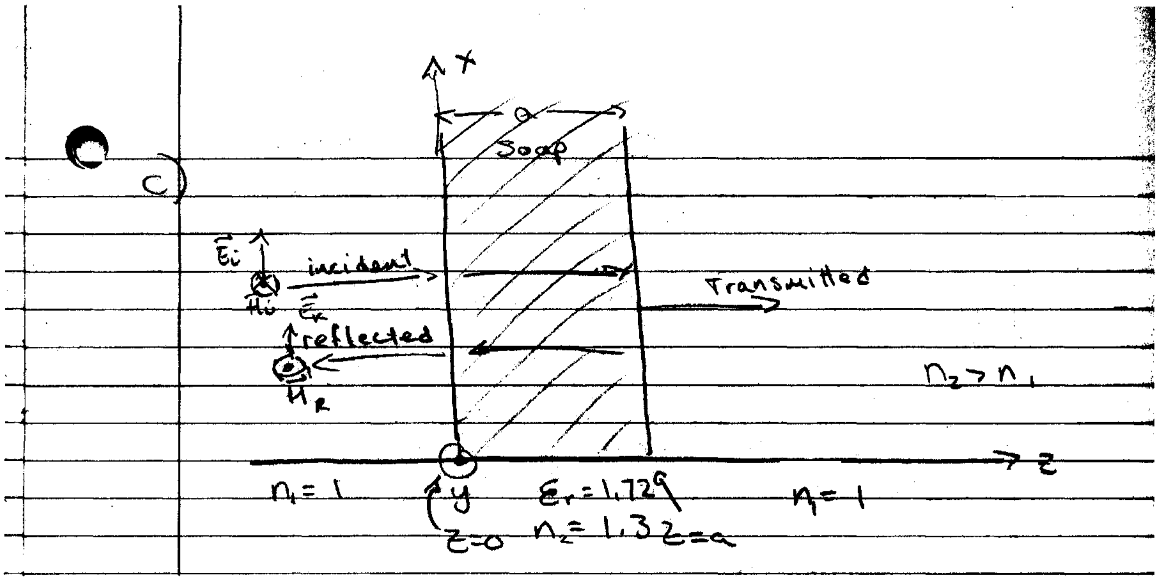
I could also use manipulation of the units in α and β to understand these quantities and how they will affect the equation for V and possibly skip step 4. Essentially I would take the equation for V for loss-less and put these variables in to account for the exp decay described in the Note.

A circuit diagram would help to determine Z_o in a manner similar to any electronics circuit problem

APPENDIX KK: PROBLEM-SOLVING INDICATORS, VARIABLES, AND CODING

Problem-Solving				
Indicator	**Variable**	**Description**	**Values**	**Problem**
Ability to recognize & acknowledge assumptions	PS_ass	Presence or identification of assumption(s)	0,1	1C
	PS_ass_Q	Quality and elaboration of assumption(s)	1,2,3, or 4	1C
Ability to translate or represent the problem into a graphical form, a sketch, or pictorial representation	PS_pic	Presence of graphical form, sketch, or pictorial representation(s)	0,1	1C
	PS_pic_Q	Quality (represdentativeness & exactness) of graphical form, sketch, or pictorial representation(s)	1,2,3, or 4	1C
Ability to translate written statements into mathematical and physical representation	PS_eqn	Presence of mathematical and/or physical representation(s)	0,1	1C
	PS_eqn_Q	Quality (represdentativeness & exactness) of mathematical and/or physical representation(s)	1,2,3, or 4	1C
Completeness & accuracy of solution	PS_sol_Q	Overall Quality of solution (regardless of the plan)	1,2,3, or 4	1C
Problem-solving		**Overall Index of Problem-Solving Ability**	**Calculation and Standardization /100**	

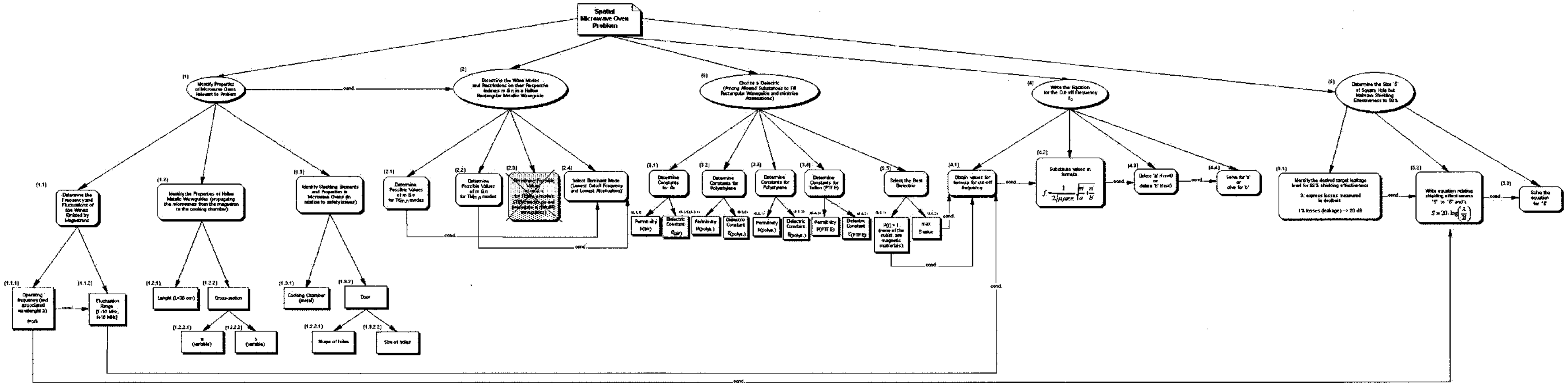
APPENDIX LL: EXAMPLE OF A REPRESENTATIVE GRAPH



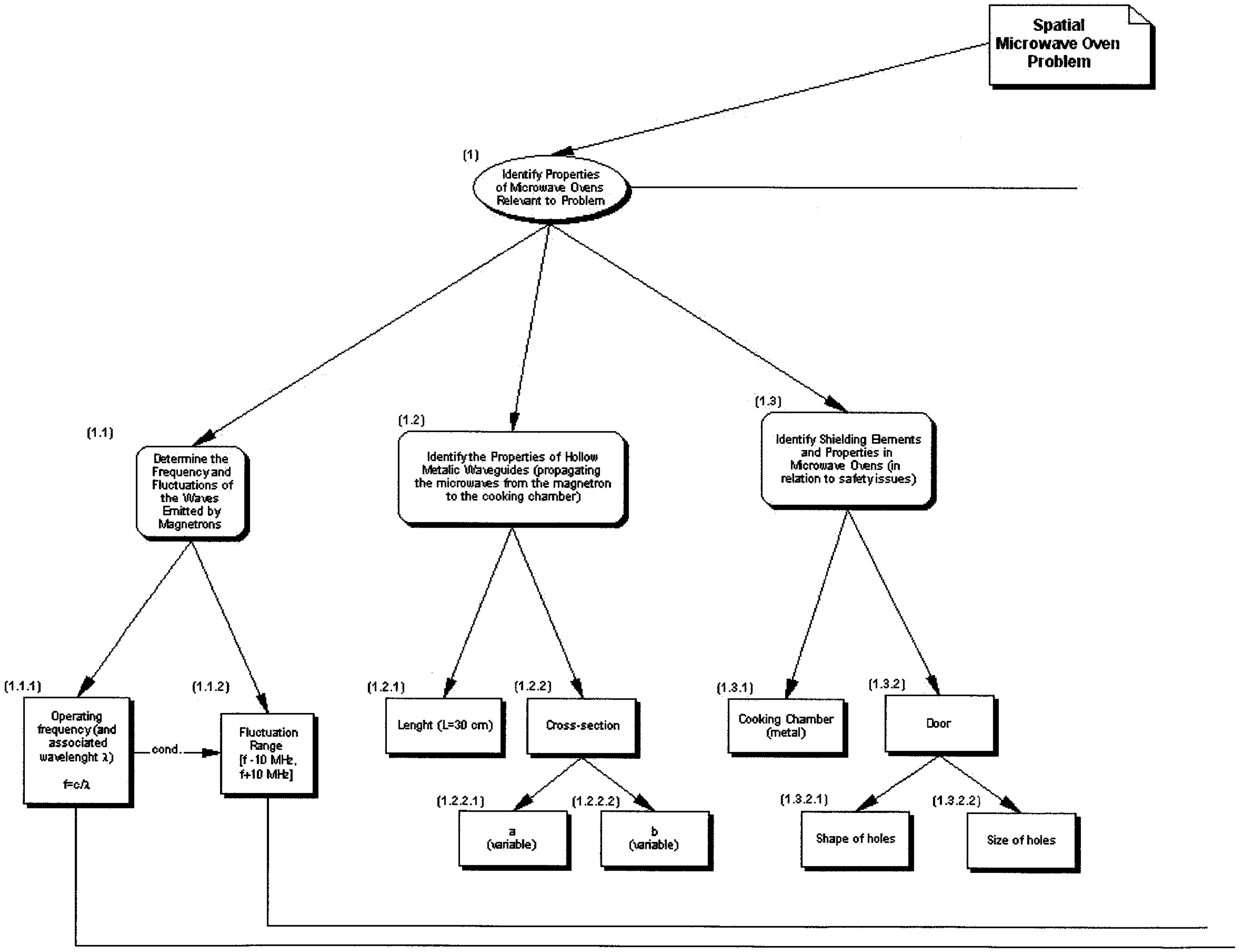
APPENDIX MM: SIMPLIFIED TRANSCRIPTION CONVENTIONS

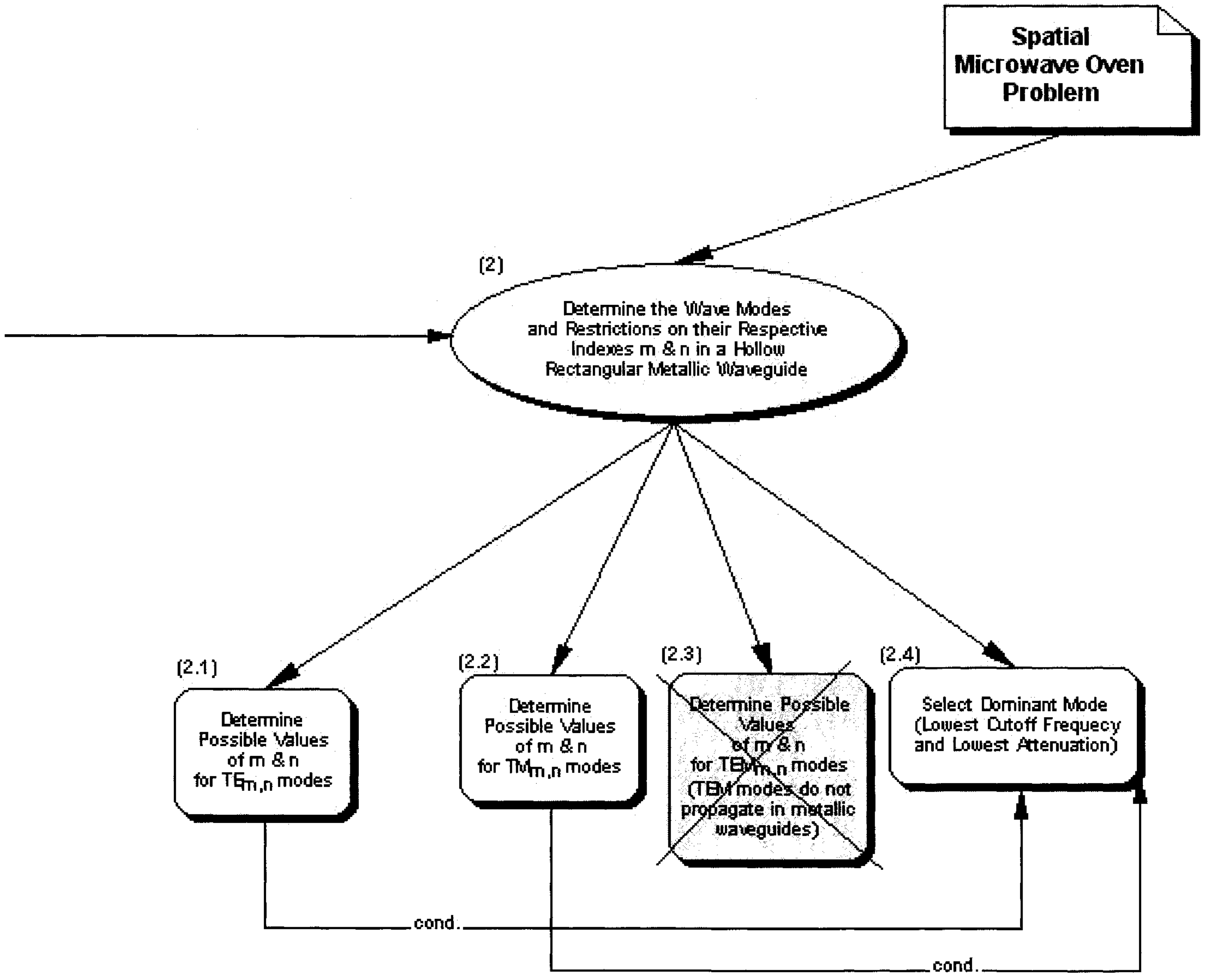
Symbol	Function
(word)	Parenthesized words are possible hearings. The best guess the transcriber could come up with.
()	Empty parentheses indicate the transcriber's inability to hear what was said
(.)	A dot in parentheses indicates a tiny gap of the order of one-tenth of a second.
<u>word</u>	Underscoring indicates some for m of stress, via pitch or amplitude
(( ))	Double parentheses contain author's description rather than transcription
*	Precede each line of comments or subtitles added by the transcriber but that is to be ignored in the analysis.
?	Indicate a rising intonation just like in natural questions
.	Indicate a stopping fall in tone similar to the end of a sentence
...	Indicate an unfinished thought

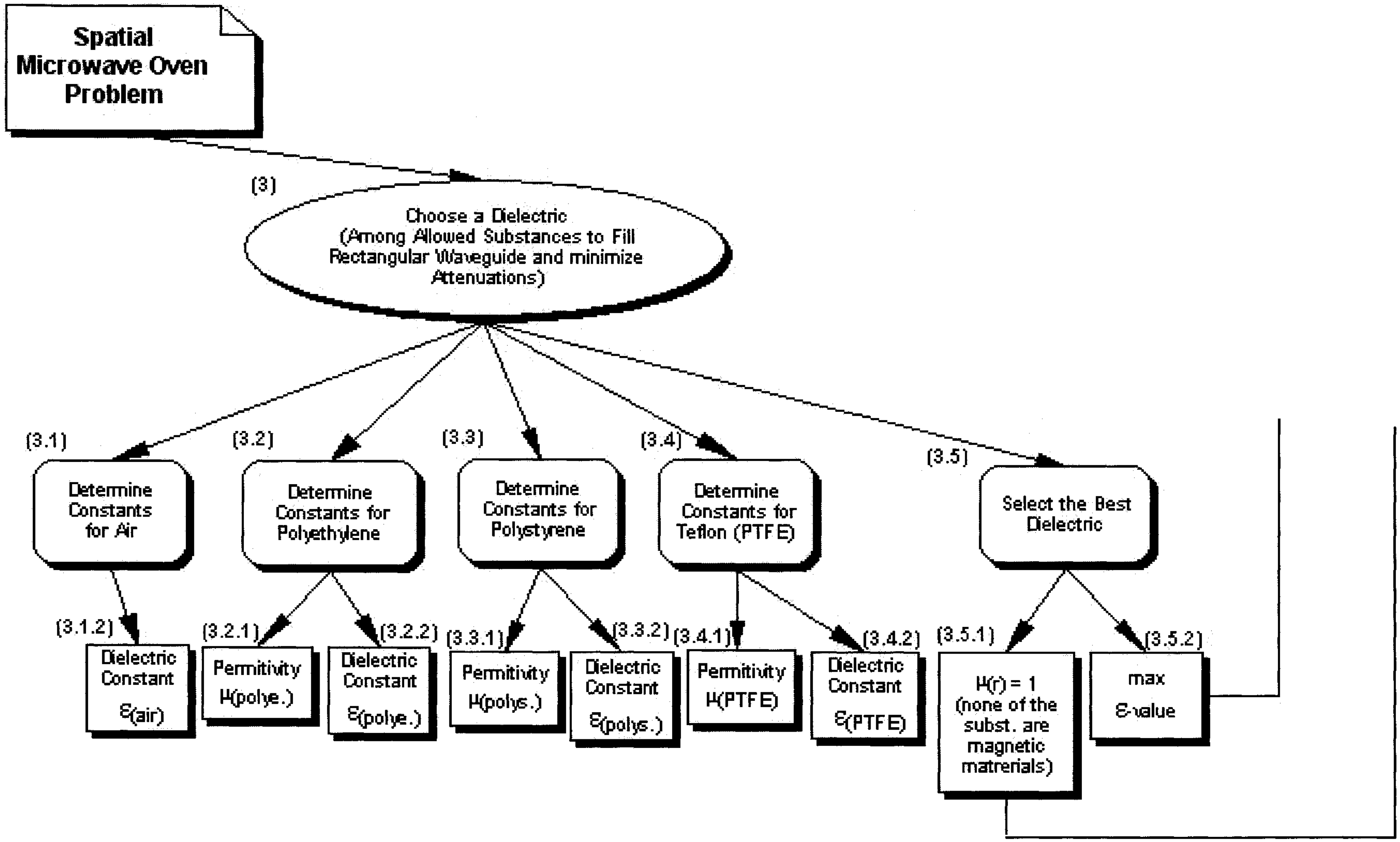
APPENDIX NN: PBL PROBLEM FRAME

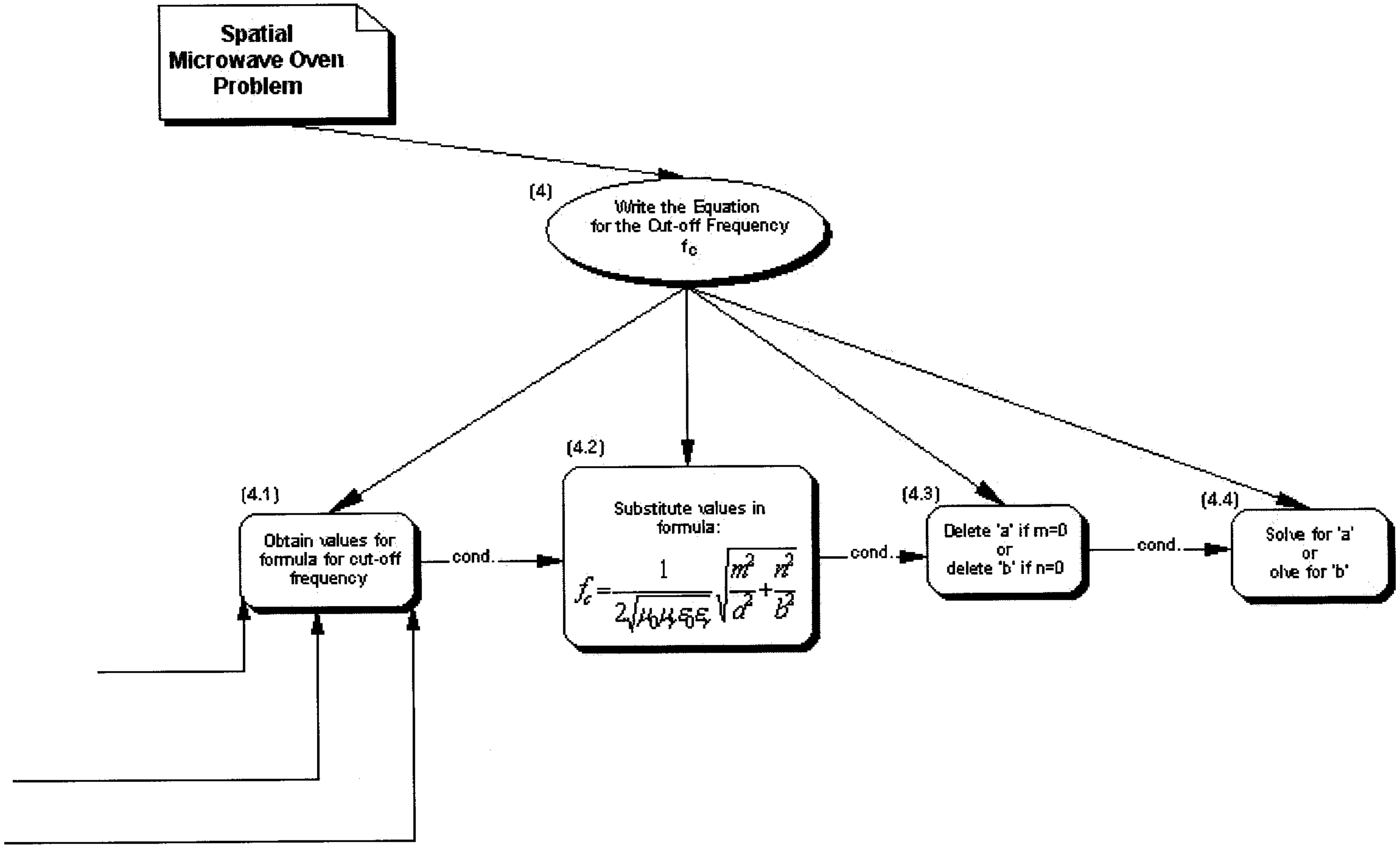


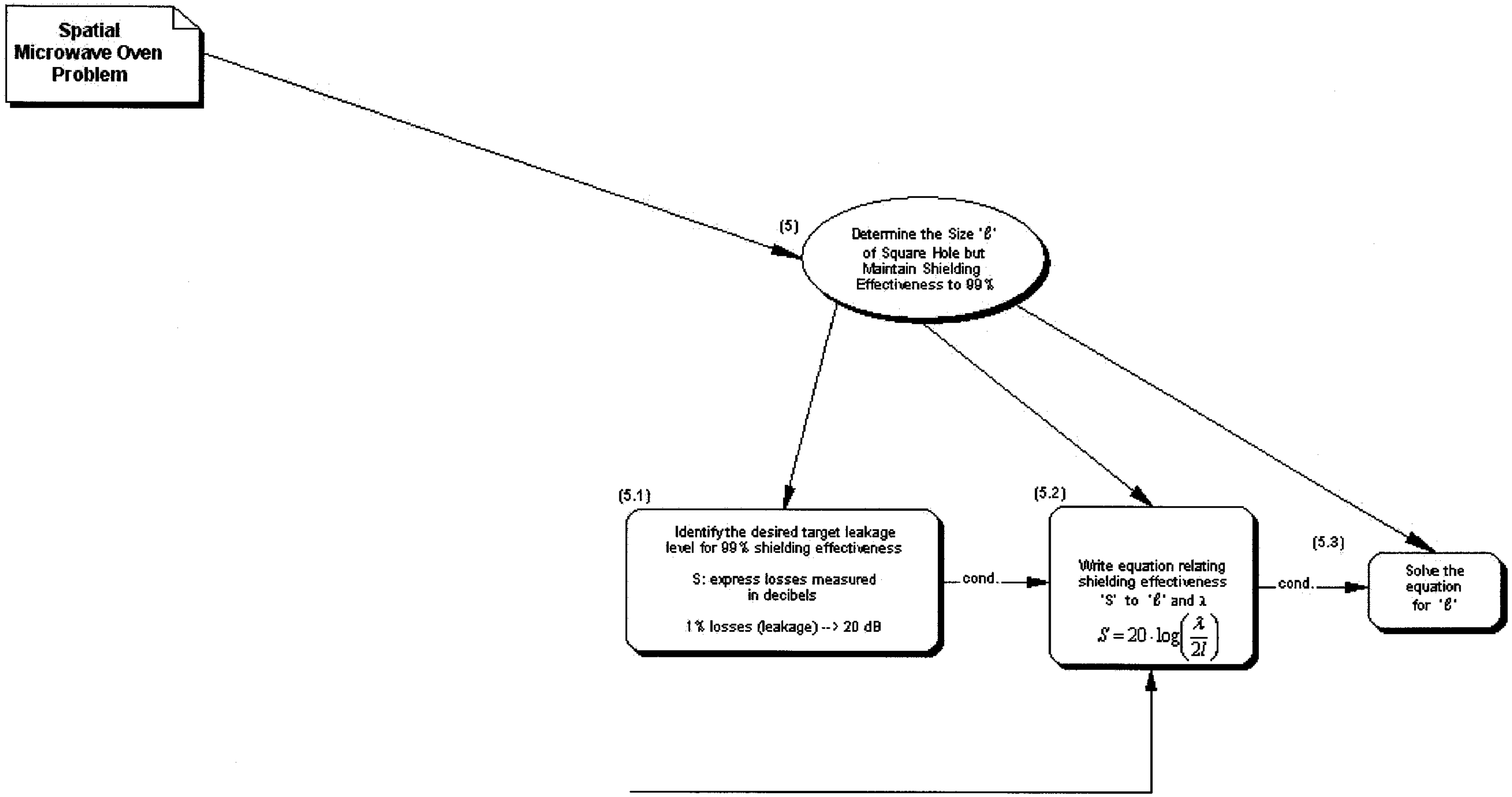
Note: The five main nodes are enlarged and presented in the following pages.


Spatial Microwave Oven Problem
(1)
Identify Properties of Microwave Ovens Relevant to Problem
(1.1)
Determine the Frequency and Fluctuations of the Waves Emitted by Magnetrons
(1.2)
Identify the Properties of Hollow Metalic Waveguides (propagating the microwaves from the magnetron to the cooking chamber)
(1.3)
Identify Shielding Elements and Properties in Microwave Ovens (in relation to safety issues)
(1.1.1)
Operating frequency (and associated wavelenght λ)
f=c/λ
cond.
(1.1.2)
Fluctuation Range
[f -10 MHz, f+10 MHz]
(1.2.1)
Lenght (L=30 cm)
(1.2.2)
Cross-section
(1.2.2.1)
a
(variable)
(1.2.2.2)
b
(variable)
(1.3.1)
Cooking Chamber (metal)
(1.3.2)
Door
(1.3.2.1)
Shape of holes
(1.3.2.2)
Size of holes


Spatial Microwave Oven Problem
(2)
Determine the Wave Modes and Restrictions on their Respective Indexes m & n in a Hollow Rectangular Metallic Waveguide
(2.1)
Determine Possible Values of m & n for $TE_{m,n}$ modes
(2.2)
Determine Possible Values of m & n for $TM_{m,n}$ modes
(2.3)
~~Determine Possible Values of m & n for $TEM_{m,n}$ modes (TEM modes do not propagate in metallic waveguides)~~
(2.4)
Select Dominant Mode (Lowest Cutoff Frequecy and Lowest Attenuation)
cond.
cond.


Spatial Microwave Oven Problem
(3)
Choose a Dielectric (Among Allowed Substances to Fill Rectangular Waveguide and minimize Attenuations)
(3.1)
Determine Constants for Air
(3.2)
Determine Constants for Polyethylene
(3.3)
Determine Constants for Polystyrene
(3.4)
Determine Constants for Teflon (PTFE)
(3.5)
Select the Best Dielectric
(3.1.2)
Dielectric Constant ε(air)
(3.2.1)
Permitivity μ(polye.)
(3.2.2)
Dielectric Constant ε(polye.)
(3.3.1)
Permitivity μ(polys.)
(3.3.2)
Dielectric Constant ε(polys.)
(3.4.1)
Permitivity μ(PTFE)
(3.4.2)
Dielectric Constant ε(PTFE)
(3.5.1)
μ(r) = 1 (none of the subst. are magnetic matrerials)
(3.5.2)
max ε-value


Spatial Microwave Oven Problem
(4)
Write the Equation for the Cut-off Frequency f_c
(4.1)
Obtain values for formula for cut-off frequency
cond.
(4.2)
Substitute values in formula:
$f_c=\frac{1}{2\sqrt{\mu_0\mu\varepsilon_0\varepsilon}}\sqrt{\frac{m^2}{a^2}+\frac{n^2}{b^2}}$
cond.
(4.3)
Delete 'a' if m=0 or delete 'b' if n=0
cond.
(4.4)
Solve for 'a' or olve for 'b'


Spatial Microwave Oven Problem
(5)
Determine the Size 'ℓ' of Square Hole but Maintain Shielding Effectiveness to 99%
(5.1)
Identify the desired target leakage level for 99% shielding effectiveness
S: express losses measured in decibels
1% losses (leakage) --> 20 dB
cond.
(5.2)
Write equation relating shielding effectiveness 'S' to 'ℓ' and λ
$S = 20 \cdot \log\left(\frac{\lambda}{2l}\right)$
cond.
(5.3)
Solve the equation for 'ℓ'

APPENDIX OO: CODEBOOK

(1) /Problem Frame

- (1 1) /Identify Microwave Properties
    - (1 1 1) /Determine Magnetron Frequency & Fluctuations
        - (1 1 1 1) /Operating frequency & wavelength
        - (1 1 1 2) /Fluctuation range
    - (1 1 2) /ID Hollow Metal Waveguide Prop
        - (1 1 2 1) /Length L=30 cm
        - (1 1 2 2) /Cross-section
            - (1 1 2 2 1) /a
            - (1 1 2 2 2) /b
    - (1 1 3) /Identify Shielding Element & Prop
        - (1 1 3 1) /Cooking Chamber
        - (1 1 3 2) /Door and or Mesh Feature
            - (1 1 3 2 1) /Shape of Holes
            - (1 1 3 2 2) /Size of Holes

- (1 2) /Determine Wave Modes in Waveguides
    - (1 2 1) /Determine m & n for TE modes
    - (1 2 2) /Determine m & n for TM modes
    - (1 2 3) /Determine m & n for TEM modes
    - (1 2 4) /Select Dominant Mode

- (1 3) /Choose Dielectric
    - (1 3 1) /Determine Air Constants
        - (1 3 1 1) /Permitivity μ Air
        - (1 3 1 2) /Dielectric Const Air
    - (1 3 2) /Determine Polyethylene Constants
        - (1 3 2 1) /Permitivity μ Polyethylene
        - (1 3 2 2) /Dielectric Const Polyethylene
    - (1 3 3) /Determine Polystyrene Constants
        - (1 3 3 1) /Permitivity μ Polystyrene
        - (1 3 3 2) /Dielectric Const Polystyrene
    - (1 3 4) /Determine Teflon Constants
        - (1 3 4 1) /Permitivity μ Teflon
        - (1 3 4 2) /Dielectric Const Teflon
    - (1 3 5) /Select Best Dielectric
        - (1 3 5 1) /μ
        - (1 3 5 2) / Max Dielectric Const
- (1 4) /Write Cut-off Freq Equation
    - (1 4 1) /Obtain Values for Cut-off Freq
    - (1 4 2) /Substitute Values in Fc Formula
    - (1 4 3) /Delete a or b if m or n = 0
    - (1 4 4) /Solve for a or b

(1 5) /Determine Size L of Hole
    (1 5 1) /Identify Target Leakage
    (1 5 2) /Write Shielding Equation
    (1 5 3) /Solve for L

(3) /Cognitive Actions

Description: Types of cognitive activities in applying a procedure to solve a problem or a component of a problem (a sub-problem).

(3 1) /INTERPRET STATE

Description: Interpret the current problem state and situation: the problem state that occurs before a procedure has been executed (i.e., the initial state), an intermediate state or states that arise during application of a procedure or reasoning, or the problem state resulting from the application of a procedure or reasoning (i.e., the resulting state).

(3 2) /PLAN

Description: State a goal, intention to apply a procedure, or plan its application

(3 2 1) /PLAN GOAL

Description: Plan or select a goal or goals to be achieved by applying a particular problem solving procedure or procedures.

(3 2 2) /PLAN ACTION

Description: Plan an action or sequence of actions to be carried out to achieve a goal or goals.

(3 3) /TEST CONDITIONS

Description: State critical conditions for applying a procedure and decide whether the conditions required to apply a procedure have been met.

(3 4) /EXECUTE ACTION

Description: Execute a procedure by performing its actions.

(3 5) /EVALUATE

Description: Evaluate the results (solution) obtained from applying a procedure or by reasoning to derive the solution, and/or evaluate the method(s) or reasoning that was/were used to obtain the results.

(3 6) /EXPLAIN

Description: Explain the theoretical/conceptual rationale or knowledge that underlies the methods and/or reasoning processes that are used to derive the solution, or to predict, explain or evaluate the significance of the results obtained..

(3 6 1) /Explain Procedure
Description: Explain the rationale for or reasons underlying a procedure.

(3 6 2) /Explain Results
Description: Predict or explain the result obtained from applying a procedure.

(3 6 3) /Explain Theory
Description: Explain the concepts or theory underlying a procedure.

(3 7) /CORRECT
Description: Correct an error or provide a missing component of the solution.

(3 8) /REASON
Description: Use reasoning to: plan a goal or an action, interpret the problem state, infer or derive the solution (or a component of a solution), evaluate the methods used and/or the result obtained, or correct an error.

(4) /TUTORING
(4 1) /Tutoring Strategies
Description: Strategy used to convey information about the procedure to the student.

(4 1 1) /QUESTION
Description: Question requiring procedural or declarative information or explanation

(4 1 2) /INSTRUCT
Description: Instruction in actions or reasoning using proc. or dec. knowledge

(4 1 3) /HINT
Description: Clues or hints providing partial info. to help student

(4 1 4) /EXPLAIN
Description: Theory, rationale, explanation or interpretation

(4 1 5) /TELL
Description: Present descriptive information about a procedure or concept

(4 1 6) /DEMO
Description: Demonstrations that model procedures or reasoning processes

(4 1 7) /CHECK
Description: Check students reception or comprehension of information

(4 1 8) /EVALUATE

Description: Tutor evaluates results, actions or verbal productions of student or self

(4 1 9) /REQUEST

Description: Request that student apply a procedure, reason or explain

(4 1 10) /Q&A

Description: Ask and then answer own questions

(4 1 11) /RESPOND

Description: Respond to student-initiated question or request

(4 1 12) /ADVANCED ORGANIZER

Description: Organizer to guide student through dialogue/material

(4 1 13) /CLARIFY

Description: Correct or augment student's incomplete r incorrect knowledge

(4 1 14) /REPEAT or ELABORATE

Description: Repeat or elaborate information

(4 1 15) /METACOG

Description: Describe metacognitive strategies, tricks, or methods

(4 1 16) /PED STRAT

Description: Tutor describes a learning or pedagogical strategy

(5) /SPEAKER

(5 1) /TUTOR
(5 2) /STUDENT
    (5 2 1) /STUD1
    (5 2 2) /STUD2
    (5 2 3) /STUD3
    (5 2 4) /STUD4
(5 3) /FLIP_CHART
(5 4) /PROBLEM_TEXT
(5 5) /SHIELDING_TEXT
(5 6) /RESEARCHER

(7) /Type of Activity

- (7 1) /Solving the Problem
- (7 2) /Working on Learning Issues
  - (7 2 1) /Information
    - (7 2 1 1) /Processing current info or discussing prior knowledge
    - (7 2 1 2) /Sharing Findings
  - (7 2 2) /Location
    - (7 2 2 1) /During Session
    - (7 2 2 2) /Outside Session
  - (7 2 3) /Identifying a Learning Issue
- (7 3) /PBL Tasks or Assignments
  - (7 3 1) /Dialogue on tasks or organisation of work
  - (7 3 2) /Tasks they assign to themselves
  - (7 3 3) /Logistics (low level)
  - (7 3 4) /Summarize Progresses

APPENDIX PP: MULTIVARIATE OVERALL ANALYSIS OF VARIANCE FOR THE MAJOR AND HONOURS COHORT WITH THE SIX SCALES AS VARIABLES

Multivariate Tests

	Value	F	Hypothesis df	Error df	Sig.
Wilks' lambda	.823	1.363 (a)	6.000	38.000	.254
Pillai's trace	.177	1.363 (a)	6.000	38.000	.254
Hotelling's trace	.215	1.363 (a)	6.000	38.000	.254
Roy's largest root	.215	1.363 (a)	6.000	38.000	.254

(a) Exact statistic

APPENDIX QQ: UNIVARIATE ANALYSIS OF VARIANCE FOR THE MAJOR AND HONOURS COHORT ON THE SIX SCALES

Univariate Tests

Scale (Dependant Variable)		Sum of Squares	df	Mean Square	F	Sig.
Comfort in Program	Contrast	3.100	1	3.100	2.884	.097
	Error	46.230	43	1.075		
Prep. for Exam & PS	Contrast	.074	1	.074	.178	.675
	Error	17.973	43	.418		
Staying Up-to-date	Contrast	.175	1	.175	.119	.732
	Error	63.286	43	1.472		
Get the Best Out of Class	Contrast	0.984	1	.984	1.346	.252
	Error	31.433	43	.731		
Commit. & Self-discipl.	Contrast	.734	1	.734	.433	.514
	Error	72.798	43	1.693		
Physics' for all	Contrast	1.111	1	1.111	1.113	.297
	Error	42.924	43	.998		

APPENDIX RR: MULTIVARIATE OVERALL ANALYSIS OF VARIANCE FOR THE MAJOR AND HONOURS COHORT WITH INDIVIDUAL ITEMS AS VARIABLES

Multivariate Tests

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	,865	1,511(a)	34,000	8,000	,279
Wilks' lambda	,135	1,511(a)	34,000	8,000	,279
Hotelling's trace	6,420	1,511(a)	34,000	8,000	,279
Roy's largest root	6,420	1,511(a)	34,000	8,000	,279

(a) Exact statistic

APPENDIX SS: UNIVARIATE ANALYSIS OF VARIANCE FOR THE MAJOR AND HONOURS COHORT ON THE THIRTY-FOUR ITEMS

Univariate Tests

Dependent Variable (Survey Item)		Sum of Squares	df	Mean Square	F	Sig.
S01_11	Contrast	9.431	1	9.431	3.541	.067
	Error	114.528	43	2.663		
S01_50	Contrast	2.789	1	2.789	1.529	.223
	Error	78.411	43	1.824		
S01_73	Contrast	3.026	1	3.026	2.295	.137
	Error	56.693	43	1.318		
S01_64	Contrast	6.749	1	6.749	3.146	.083
	Error	92.229	43	2.145		
S01_43	Contrast	5.125	1	5.125	2.281	.138
	Error	96.621	43	2.247		
S01_52	Contrast	.000	1	.000	.000	1.000
	Error	124.000	43	2.884		
S01_45	Contrast	.967	1	.967	.328	.570
	Error	126.912	43	2.951		
S02_28	Contrast	8.705	1	8.705	3.250	.078
	Error	115.167	43	2.678		
S02_71	Contrast	.032	1	.032	.018	.893
	Error	75.168	43	1.748		
S02_58	Contrast	3.492	1	3.492	.977	.328
	Error	153.708	43	3.575		
S02_32	Contrast	6.700	1	6,700	2.861	.098
	Error	100.708	43	2.342		
S02_70	Contrast	7.239	1	7.239	2.382	.130
	Error	130.672	43	3.039		
S03_53	Contrast	.812	1	.812	.231	.633
	Error	151.099	43	3.514		
S03_65	Contrast	.332	1	.332	.134	.716
	Error	106.868	43	2.485		
S03_14	Contrast	.612	1	.612	.254	.617
	Error	103.700	43	2.412		
S03_15	Contrast	.000	1	.000	.000	.994
	Error	151.644	43	3.527		
S03_72	Contrast	1.722	1	1.722	.516	.476
	Error	143.478	43	3.337		
S03_49	Contrast	12.040	1	12.040	5.689	.022
	Error	91.012	43	2.117		

Dependent Variable (Survey Item)		Sum of Squares	df	Mean Square	F	Sig.
S05_19	Contrast	5.337	1	5.337	3.075	.087
	Error	74.631	43	1.736		
S05_66	Contrast	13.822	1	13.822	4.681	.036
	Error	126.978	43	2.953		
S05_39	Contrast	9.317	1	9.317	3.014	.090
	Error	132.935	43	3.092		
S06_24	Contrast	.028	1	.028	.013	.910
	Error	92.484	43	2.151		
S06_25	Contrast	2.883	1	2.883	.962	.332
	Error	128.829	43	2.996		
S06_26	Contrast	1.080	1	1.080	.392	.535
	Error	118.437	43	2.754		
S15_33	Contrast	.434	1	.434	.200	.657
	Error	93.472	43	2.174		
S15_36	Contrast	.300	1	.300	.096	.758
	Error	134.113	43	3.119		
S15_68	Contrast	10.717	1	10.717	3.218	.080
	Error	143.194	43	3.330		

Note on the item labels: the variable S01_11 corresponds to the original item number 11 in the administered questionnaire which subsequently became a part of the first scale (S01), the variable S15_36 corresponds to the original item number 36 in the administered questionnaire which subsequently became a part of the fifteenth scale (S15), etc.

APPENDIX TT: SUMMARY TABLE FOR INSTRUCTIONAL TECHNIQUE

Techniques	Obs Dates	Jan 23	Jan 30	Feb 09	Mar 12	Mar 15	Mar 17	Mar 24	Mar 26	Mar 29	Mar 31	Apr 02	Apr 05	Apr 07
Plan	Presence	Y	Y	Y	N	N	Y	N	N	N	N	N	Y	N
	Adequacy	1	1	1	N/A	N/A	1	N/A	N/A	N/A	N/A	N/A	1	N/A
Schemas & Graphs	Number	4	7	6	4	10	8	7	3	2	5	3	10	17
	Adequacy	3.00	2.86	3.00	3.00	3.00	2.88	3.00	3.00	3.00	3.00	3.00	2.90	2.59
Asking Questions	Number	5	8	4	6	9	4	8	6	4	13	5	5	3
	Adequacy	2.40	2.38	2.50	2.67	2.56	2.25	2.38	2.50	2.25	2.92	2.20	2.40	2.33
Enough Time	Number	4	6	3	5	7	4	8	5	3	13	2	5	3
Students Questions	Number	3	10	6	11	7	6	2	6	3	3	3	6	4
	Adequacy	2.67	2.30	2.33	2.45	2.43	1.67	2.50	2.33	3.00	3.00	2.67	2.83	3.00
Professor's Answers	Number	3	10	6	11	7	6	2	6	3	3	3	6	4
	Adequacy	3.00	2.90	2.50	2.45	3.00	2.33	3.00	2.17	3.00	2.33	2.33	2.67	3.00
Examples & Applications	Number	5	7	7	2	8	9	6	5	3	6	5	6	6
	Adequacy	3.00	2.43	2.86	2.50	2.63	2.89	2.67	3.00	3.00	3.00	3.00	3.00	3.00
Analogies	Number	3	3	3	1	3	3	2	2	2	4	2	3	2
	Adequacy	3.00	3.00	3.00	2.00	3.00	2.67	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Anecdotes & Humor	Number	3	3	4	4	3	4	5	4	1	2	2	5	3
	Adequacy	2.00	2.33	1.75	2.25	3.00	2.00	2.40	1.75	3.00	2.00	2.50	2.80	3.00
Explicit Link w/ Prior K	Number	3	4	2	5	3	5	4	3	2	6	4	2	8
	Adequacy	2.33	2.75	3.00	2.60	2.67	3.00	3.00	2.67	2.50	3.00	3.00	3.00	3.00
Modelling	Number	4	8	3	8	4	3	3	5	4	6	4	4	6
	Adequacy	2.75	3.00	3.00	3.00	3.00	2.67	3.00	3.00	3.00	3.00	3.00	3.00	3.00

APPENDIX UU: COMPARISON OF THE TRADITIONAL AND PBL STUDENTS FOR THE PRE-TEST (MULTIVARIATE TESTS)

ffect		Value	F	Hypothesis df	Error df	Sig.	Effect
ıtercept	Pillai's Trace	.964	74.324(b)	4.000	11.000	.000	.964
	Wilks' Lambda	.036	74.324(b)	4.000	11.000	.000	.964
	Hotelling's Trace	27.027	74.324(b)	4.000	11.000	.000	.964
	Roy's Largest Root	27.027	74.324(b)	4.000	11.000	.000	.964
'BL_status	Pillai's Trace	.218	.769(b)	4.000	11.000	.568	.218
	Wilks' Lambda	.782	.769(b)	4.000	11.000	.568	.218
	Hotelling's Trace	.279	.769(b)	4.000	11.000	.568	.218
	Roy's Largest Root	.279	.769(b)	4.000	11.000	.568	.218

a Computed using alpha = ,05
b Exact statistic
c Design: Intercept+PBL_status

APPENDIX VV: COMPARISON OF THE TRADITIONAL AND PBL STUDENTS FOR THE PRE-TEST (TESTS OF BETWEEN-SUBJECTS EFFECTS)

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	Pre_Meta	208.333(b)	1	208.333	1.151	.302
	Pre_Crit	13.021(e)	1	13.021	.059	.811
	Pre_Intuit	1.439(d)	1	1.439	.004	.951
	Pre_PS	325.521(e)	1	325.521	2.059	.173
Intercept	Pre_Meta	37969.875	1	37969.875	209.721	.000
	Pre_Crit	33338.021	1	33338.021	151.270	.000
	Pre_Intuit	29582.960	1	29582.960	81.789	.000
	Pre_PS	35208.333	1	35208.333	222.682	.000
PBL_status	Pre_Meta	208.333	1	208.333	1.151	.302
	Pre_Crit	13.021	1	13.021	.059	.811
	Pre_Intuit	1.439	1	1.439	.004	.951
	Pre_PS	325.521	1	325.521	2.059	.173
Error	Pre_Meta	2534.695	14	181.050		
	Pre_Crit	3085.417	14	220.387		
	Pre_Intuit	5063.759	14	361.697		
	Pre_PS	2213.542	14	158.110		
Total	Pre_Meta	49688.917	16			
	Pre_Crit	46675.000	16			
	Pre_Intuit	44234.556	16			
	Pre_PS	45078.125	16			
Corrected Total	Pre_Meta	2743.028	15			
	Pre_Crit	3098.438	15			
	Pre_Intuit	5065.198	15			
	Pre_PS	2539.063	15			

a Computed using alpha = .05

b R Squared = .076 (Adjusted R Squared = .010)

c R Squared = .004 (Adjusted R Squared = -.067)

d R Squared = .000 (Adjusted R Squared = -.071)

e R Squared = .128 (Adjusted R Squared = .066)

APPENDIX WW: COMPARISON OF THE PRE- AND POST-TEST FOR THE TRADITIONAL STUDENTS (WITHIN-SUBJECTS)

Estimates

COG_skill	time	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
Metacognition	1	59.524	5.202	48.811	70.238
	2	63.691	4.808	53.789	73.594
Critical Thinking	1	65.714	5.202	55.001	76.428
	2	71.429	4.808	61.526	81.331
Physical Intuition	1	47.620	5.202	36.907	58.333
	2	48.810	4.808	38.908	58.712
Problem Solving	1	50.000	4.866	39.979	60.021
	2	80.469	4.498	71.206	89.732

Multivariate Tests

COG_skill		Value	F	Hypothesis df	Error df	Sig.
Metacognition	Pillai's trace	.015	.372(a)	1.000	25.000	.547
	Wilks' lambda	.985	.372(a)	1.000	25.000	.547
	Hotelling's trace	.015	.372(a)	1.000	25.000	.547
	Roy's largest root	.015	.372(a)	1.000	25.000	.547
Critical Thinking	Pillai's trace	.027	.699(a)	1.000	25.000	.411
	Wilks' lambda	.973	.699(a)	1.000	25.000	.411
	Hotelling's trace	.028	.699(a)	1.000	25.000	.411
	Roy's largest root	.028	.699(a)	1.000	25.000	.411
Physical Intuition	Pillai's trace	.001	.030(a)	1.000	25.000	.863
	Wilks' lambda	.999	.030(a)	1.000	25.000	.863
	Hotelling's trace	.001	.030(a)	1.000	25.000	.863
	Roy's largest root	.001	.030(a)	1.000	25.000	.863
Problem Solving	Pillai's trace	.476	22.721(a)	1.000	25.000	.000
	Wilks' lambda	.524	22.721(a)	1.000	25.000	.000
	Hotelling's trace	.909	22.721(a)	1.000	25.000	.000
	Roy's largest root	.909	22.721(a)	1.000	25.000	.000

Each F tests the multivariate simple effects of time within each level combination of the other effects shown. These tests are based on the linearly independent pairwise comparisons among the estimated marginal means.

a Exact statistic

APPENDIX XX: COMPARISON OF THE PRE- AND POST-TEST FOR THE PBL STUDENTS (WITHIN-SUBJECTS)

Estimates

COG_skill	time	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
Metacognition	1	60,418	7,408	44,276	76,559
	2	63,543	6,013	50,442	76,643
Critical Thinking	1	53,750	7,408	37,609	69,891
	2	68,750	6,013	55,650	81,850
Physical Intuition	1	49,998	7,408	33,856	66,139
	2	79,168	6,013	66,067	92,268
Problem Solving	1	59,375	7,408	43,234	75,516
	2	73,438	6,013	60,337	86,538

Multivarate Tests

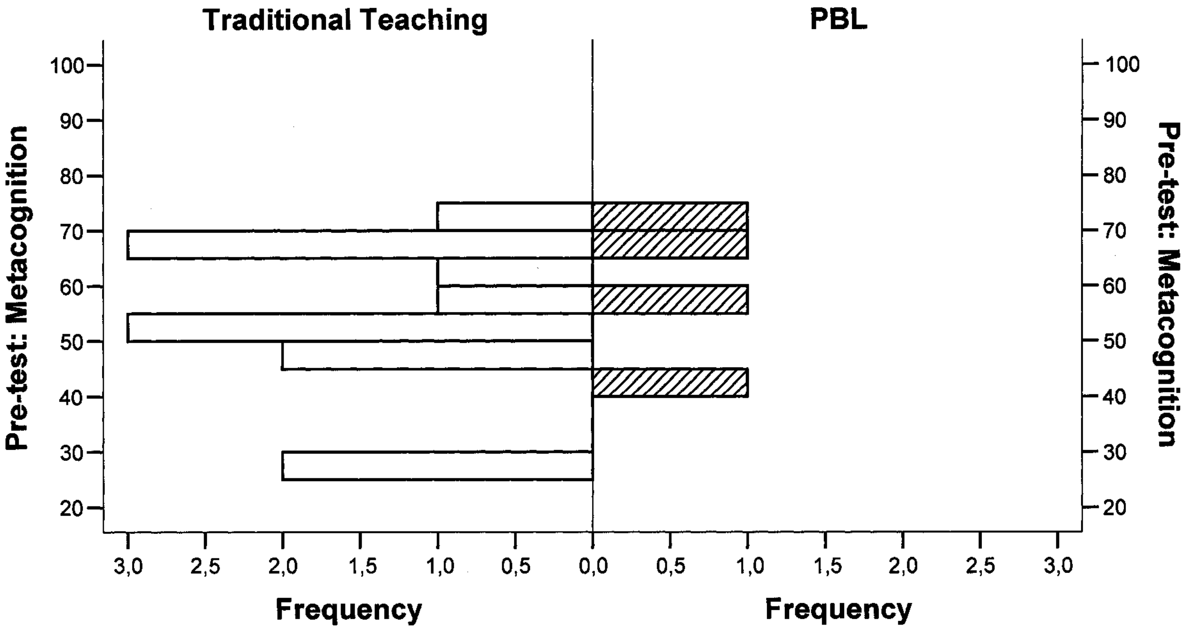
COG_skill		Value	F	Hypothesis df	Error df	Sig.
Metacognition	Pillai's trace	,007	,085(a)	1,000	12,000	,775
	Wilks' lambda	,993	,085(a)	1,000	12,000	,775
	Hotelling's trace	,007	,085(a)	1,000	12,000	,775
	Roy's largest root	,007	,085(a)	1,000	12,000	,775
Critical Thinking	Pillai's trace	,140	1,961(a)	1,000	12,000	,187
	Wilks' lambda	,860	1,961(a)	1,000	12,000	,187
	Hotelling's trace	,163	1,961(a)	1,000	12,000	,187
	Roy's largest root	,163	1,961(a)	1,000	12,000	,187
Physical Intuition	Pillai's trace	,382	7,416(a)	1,000	12,000	,018
	Wilks' lambda	,618	7,416(a)	1,000	12,000	,018
	Hotelling's trace	,618	7,416(a)	1,000	12,000	,018
	Roy's largest root	,618	7,416(a)	1,000	12,000	,018
Problem Solving	Pillai's trace	,126	1,724(a)	1,000	12,000	,214
	Wilks' lambda	,874	1,724(a)	1,000	12,000	,214
	Hotelling's trace	,144	1,724(a)	1,000	12,000	,214
	Roy's largest root	,144	1,724(a)	1,000	12,000	,214

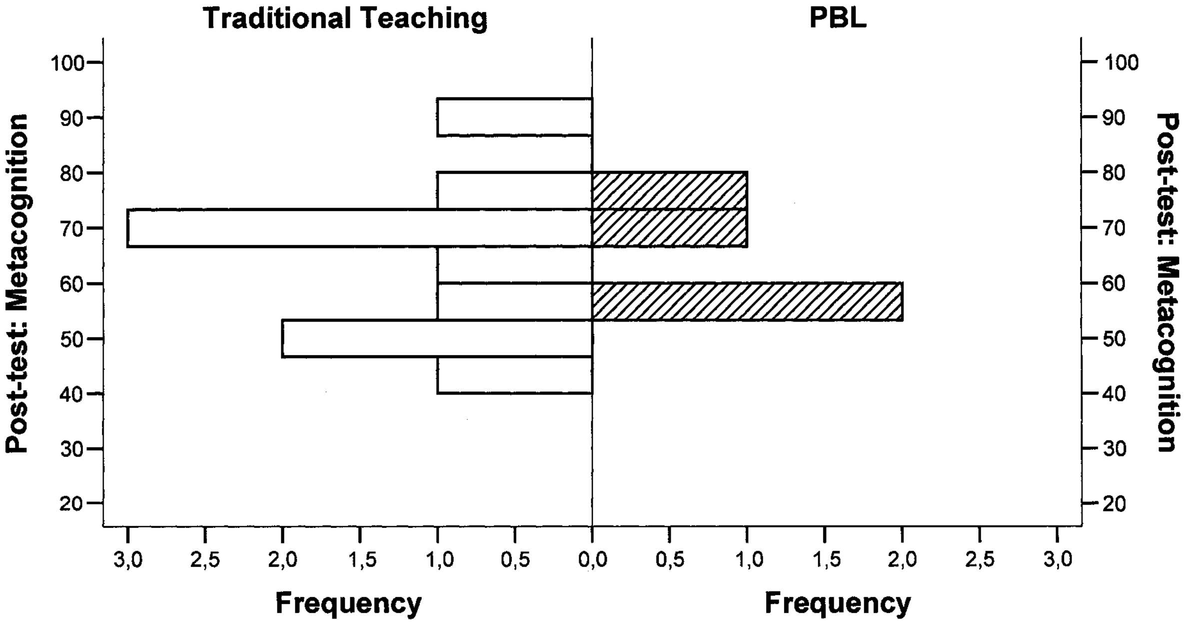
Each F tests the multivariate simple effects of time within each level combination of the other effects shown. These tests are based on the linearly independent pairwise comparisons among the estimated marginal means.

a Exact statistic

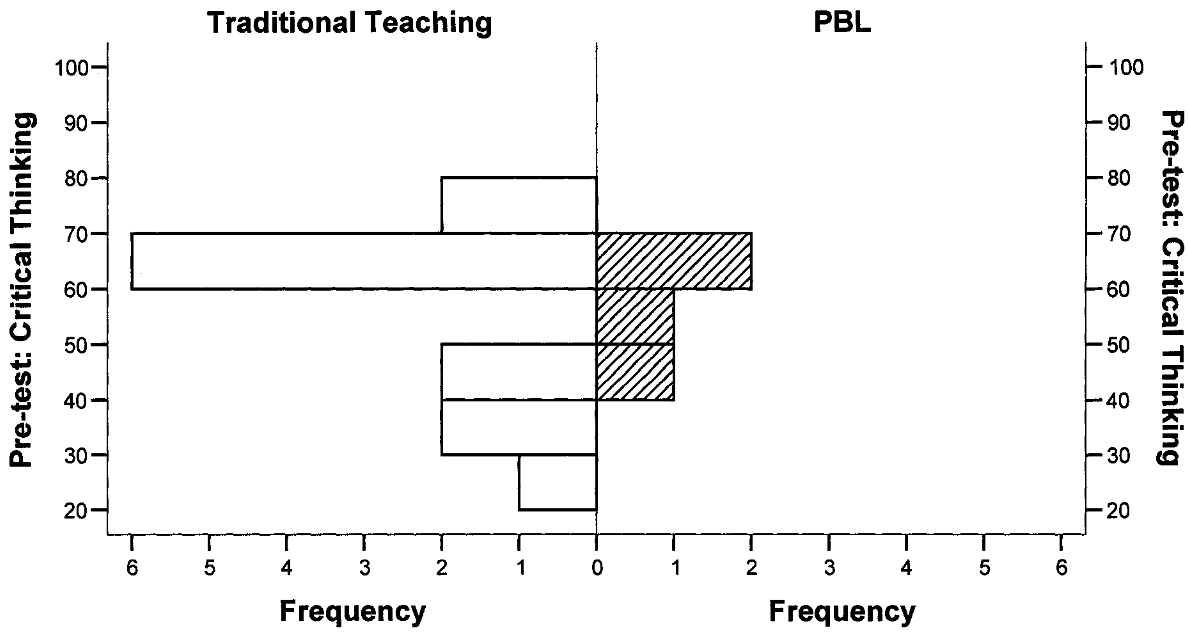
APPENDIX YY: DISTRIBUTION OF SCORES

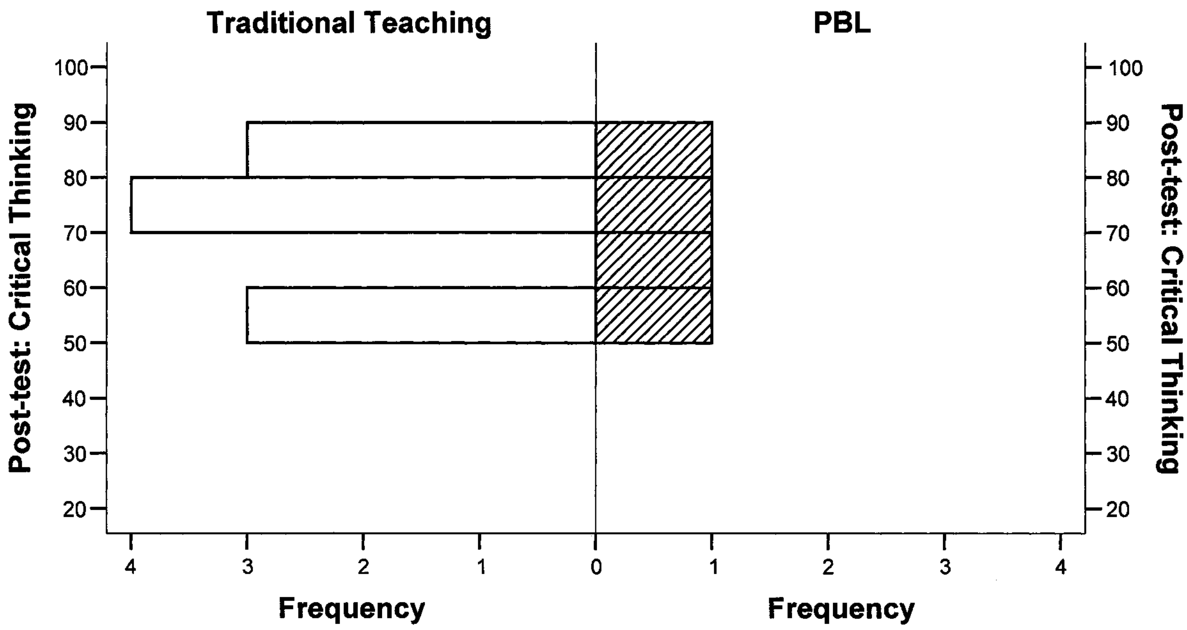
Metacognition



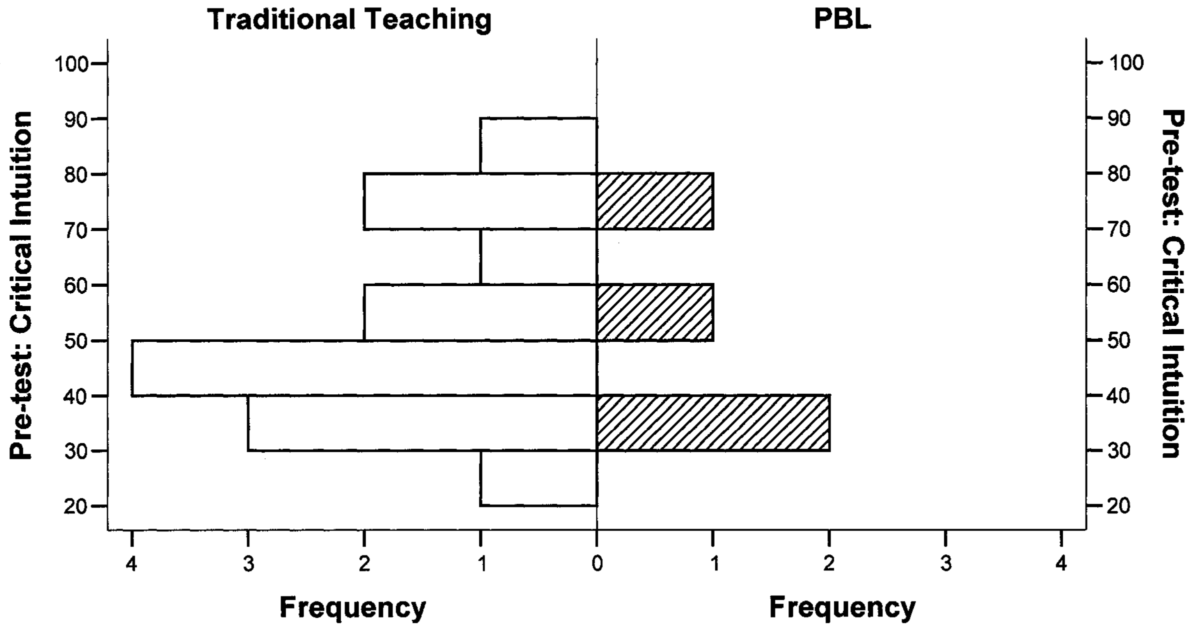


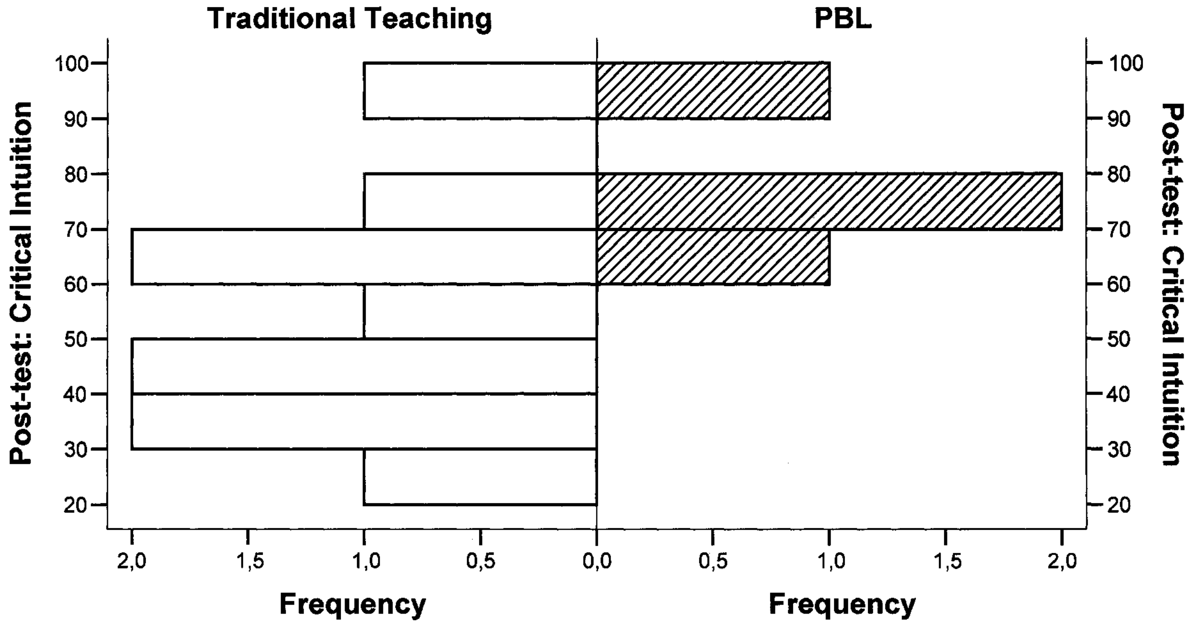
Critical Thinking

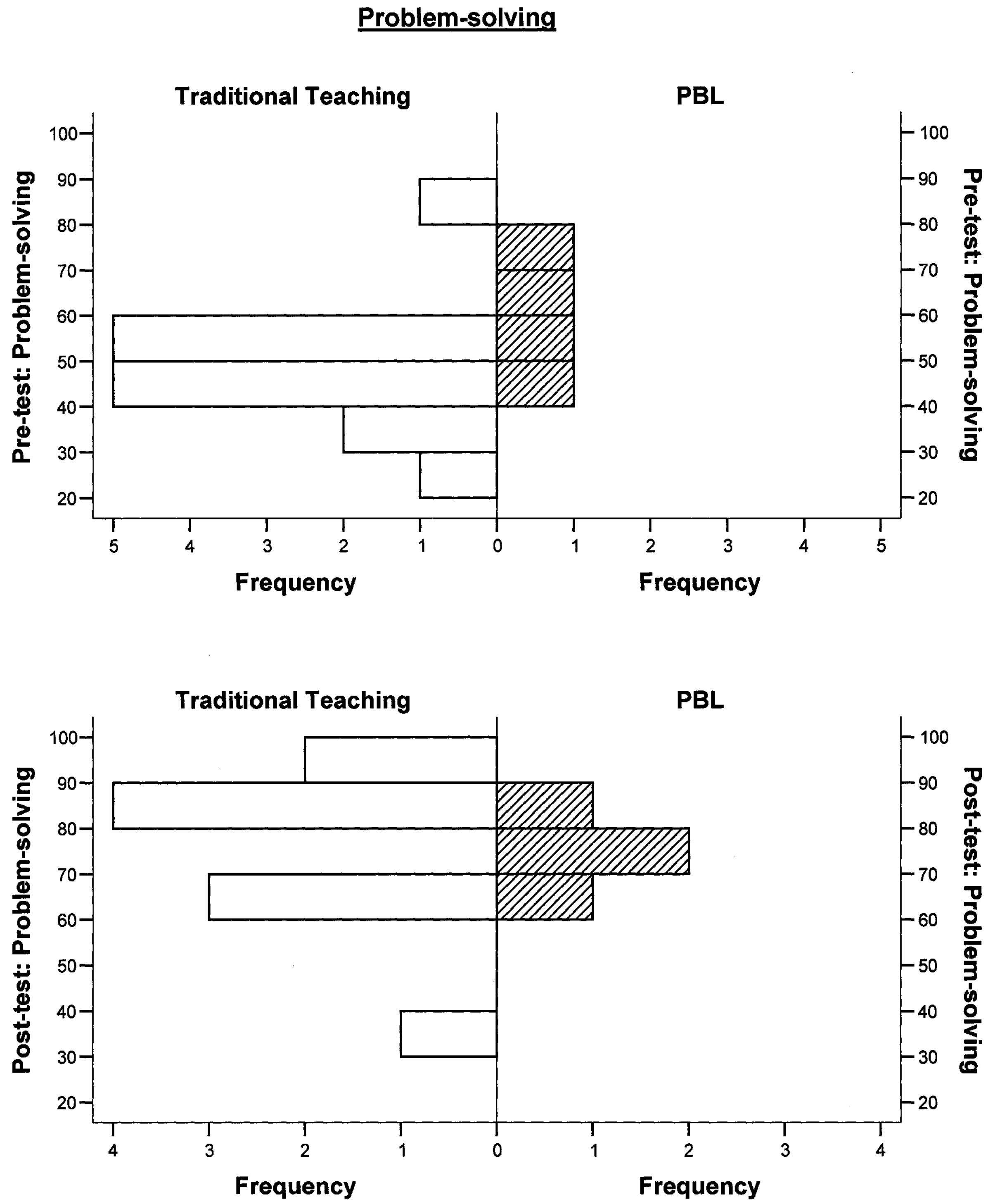




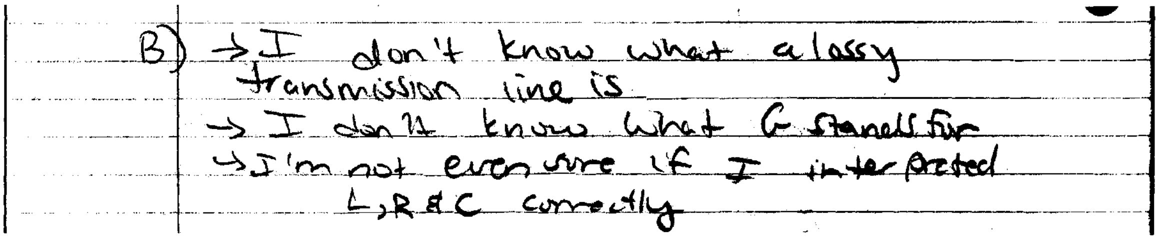
Physical Intuition






Problem-solving
Traditional Teaching
PBL
Pre-test: Problem-solving
100
90
80
70
60
50
40
30
20
5
4
3
2
1
0
1
2
3
4
5
Frequency
Frequency
Traditional Teaching
PBL
Post-test: Problem-solving
100
90
80
70
60
50
40
30
20
4
3
2
1
0
1
2
3
4
Frequency
Frequency

APPENDIX ZZ: ILLUSTRATION OF HELPLESSNESS IN THE FACE OF AN UNFAMILIAR PROBLEM (EXCERPT 1)

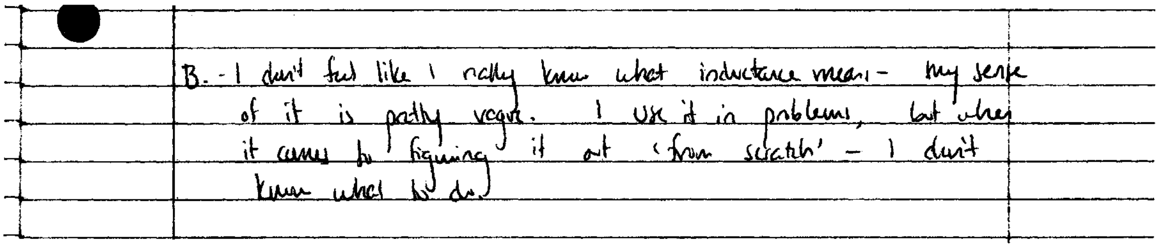


B) → I don't know what a lossy transmission line is

→ I don't know what G stands for

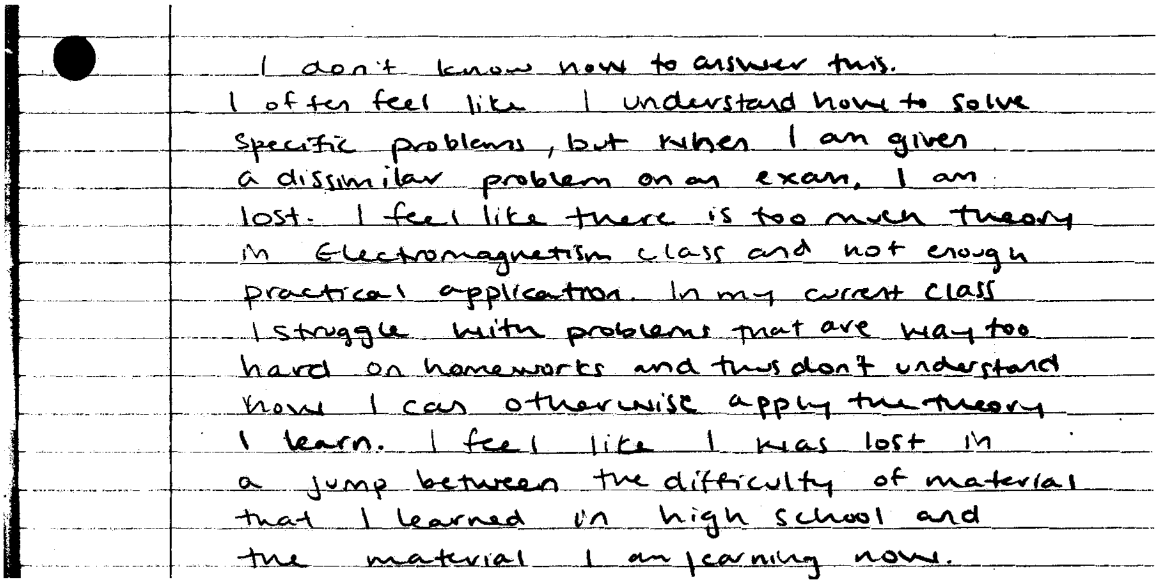
↳ I'm not even sure if I interpreted L, R & C correctly

APPENDIX AAA: ILLUSTRATION OF HELPLESSNESS IN THE FACE OF AN UNFAMILIAR PROBLEM (EXCERPT 2)



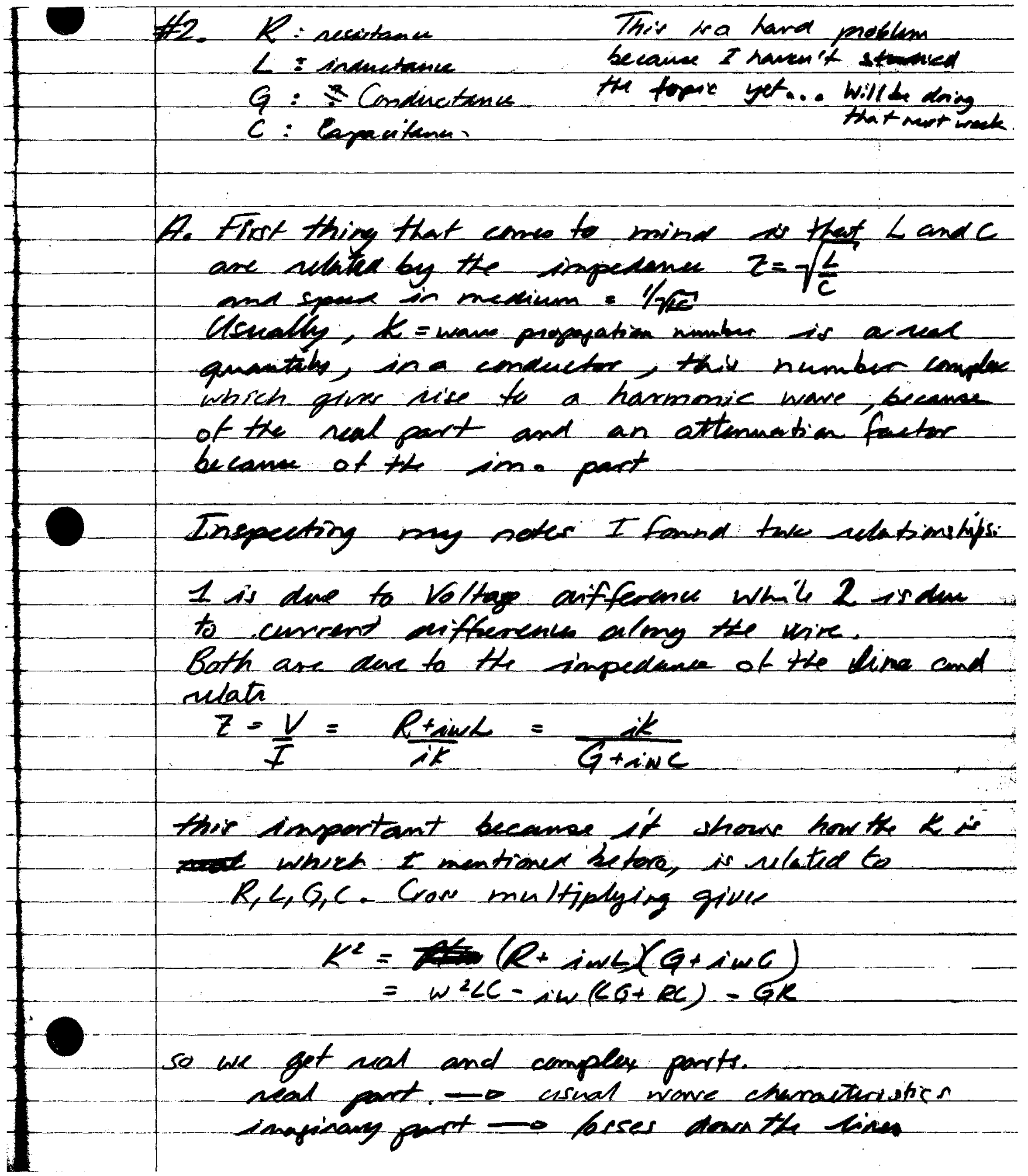
B. - I don't feel like I really know what inductance means - my sense
of it is pretty vague. I use it in problems, but when
it comes to figuring it out 'from scratch' - I don't
know what to do.

APPENDIX BBB: ILLUSTRATION OF HELPLESSNESS IN THE FACE OF AN UNFAMILIAR PROBLEM (EXCERPT 3)



I don't know how to answer this.
I often feel like I understand how to solve
specific problems, but when I am given
a dissimilar problem on an exam, I am
lost. I feel like there is too much theory
in Electromagnetism class and not enough
practical application. In my current class
I struggle with problems that are way too
hard on homeworks and thus don't understand
how I can otherwise apply the theory
I learn. I feel like I was lost in
a jump between the difficulty of material
that I learned in high school and
the material I am learning now.

APPENDIX CCC: ILLUSTRATION OF SELF-EFFICACY IN DEALING WITH AN UNFAMILIAR PROBLEM



#2. R : resistance
L : inductance
G : Conductance
C : Capacitance.

This is a hard problem because I haven't studied the topic yet... Will be doing that next week

A. First thing that comes to mind ~~is~~ that L and C are related by the impedance $Z = \sqrt{\frac{L}{C}}$ and speed in medium = $1/\sqrt{LC}$
Usually, k = wave propagation number is a real quantity, in a conductor, this number complex which gives rise to a harmonic wave, because of the real part and an attenuation factor because of the im. part

Inspecting my notes I found two relationships:

1 is due to Voltage difference while 2 is due to current differences along the wire.
Both are due to the impedance of the line and relate

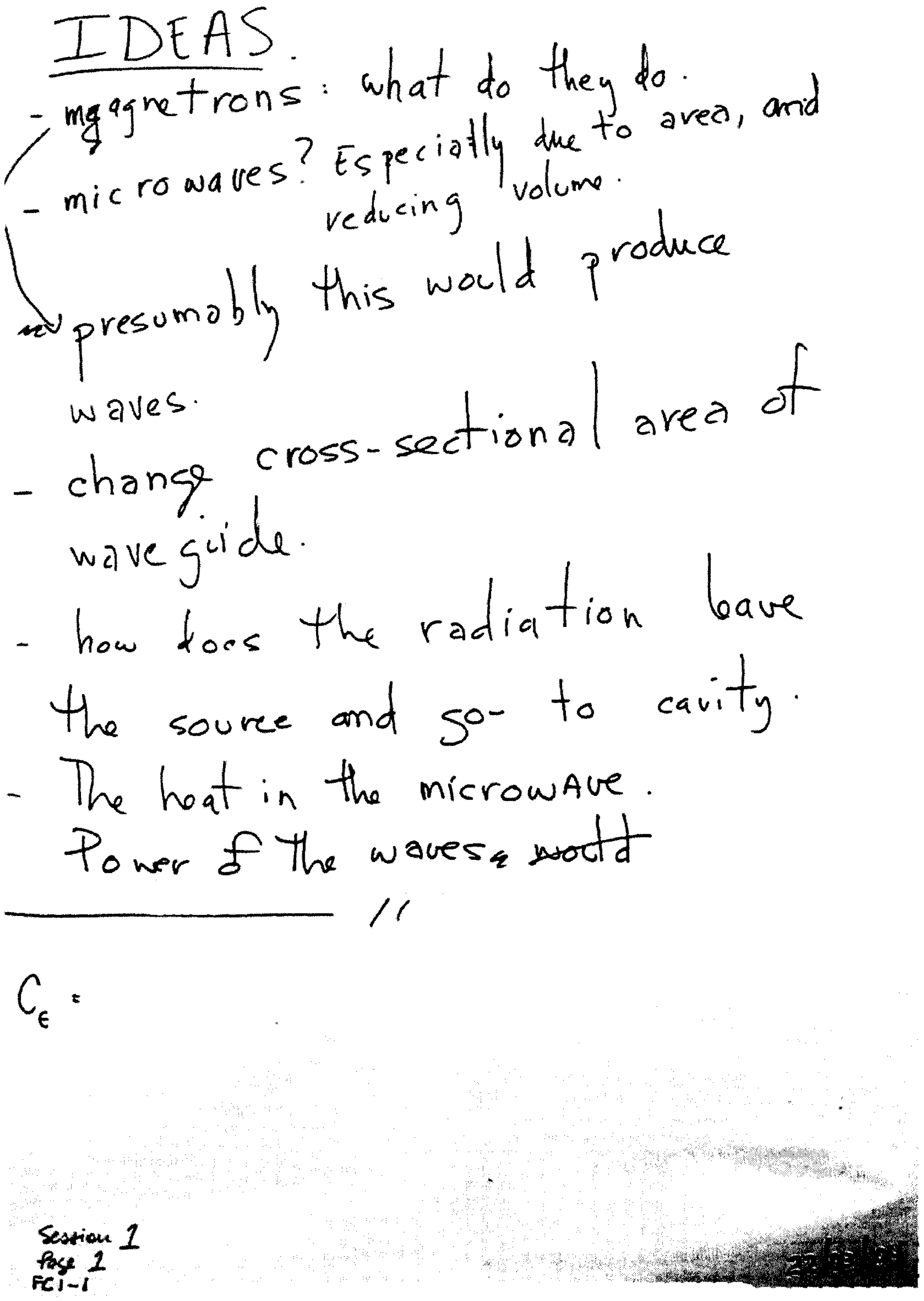
$$Z = \frac{V}{I} = \frac{R + i\omega L}{ik} = \frac{ik}{G + i\omega C}$$

this important because it shows how the k is ~~real~~ which I mentioned before, is related to R, L, G, C. Cross multiplying gives

$$K^2 = (R + i\omega L)(G + i\omega C)$$
$$= \omega^2 LC - i\omega (LG + RC) - GR$$

so we get real and complex parts.
real part. → usual wave characteristics
imaginary part → losses down the line

APPENDIX DDD: EXEMPLARS OF FLIP-CHART SHEETS PRODUCED BY THE PBL PARTICIPANTS



IDEAS.

- magnetrons: what do they do.
- microwaves? Especially due to area, and reducing volume.

→ presumably this would produce waves.

- change cross-sectional area of waveguide.
- how does the radiation leave the source and go to cavity.
- The heat in the microwAve.

Power of the waves ~~would~~

//

C_ϵ :

Session 1
Page 1
FC1-1

$$C_\epsilon = \frac{1}{\sqrt{\epsilon}} C_{f.s} \qquad \boxed{\epsilon \geq 1}$$

$$C_{f.s} = \nu \lambda_{f.s.} \qquad \sqrt{\epsilon} = n$$

$$C_\epsilon = \frac{1}{\sqrt{\epsilon}} \nu \lambda_{f.s} = \nu \lambda_\epsilon$$

$$\lambda_\epsilon = \frac{\lambda_{f.s}}{\sqrt{\epsilon}} = \frac{\lambda_{f.s}}{n}$$; n is the index of refraction.

$$\lambda_c = 2a$$

~~$\lambda_{\epsilon c} = \frac{2a}{n}$~~ ; this in then the ~~least~~ largest wavelength allowed in the waveguide

~~$\frac{n \lambda_{\epsilon c}}{2} = a$~~

relative permittivities.

polyethelyne $\epsilon_{polyeth} = 2.3$ } ~~possible~~ at optical frequencie

polystrerene $\epsilon_{polystyren} = 2.6$ }

teflon $\epsilon_{teflon} = 2.1$

$$\boxed{\frac{C_{fs}}{2\nu} = a}$$ ~~max size of~~ smallest a possible in free space.

so in a dielctric

$$\frac{C_{f.s}}{2\nu\sqrt{\epsilon}} = \frac{a}{\sqrt{\epsilon}} \Longrightarrow \frac{\sqrt{\epsilon}\, C_\epsilon}{2\nu} = a ; \sqrt{\epsilon} \geq 1$$

$$\frac{C_\epsilon}{2\nu} = \frac{a}{\sqrt{\epsilon}} = a' \; ; \; a' \leq a$$

STUD. Meet.
PAGE 2
FC5-2

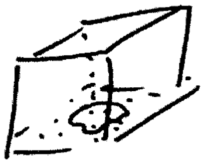
23/03/04

$\lambda_c' = \frac{2a}{\sqrt{\epsilon}}$; this is the new cutoff frequency.

$c = \nu\lambda$

$\lambda = \frac{c}{\nu} = \frac{3 \times 10^8}{2.45 \times 10^9}$

$= 12.24$ [illegible] cm



$\lambda = \frac{c\cancel{\nu}}{\nu} = 2a$

$\frac{c\cancel{\nu}}{2\nu} = a$

$a = \frac{3 \times 10^8 \text{ m/s} \cdot \cancel{2.45 \times 10^9 \text{ Hz}}}{2.45 \times 10^9 \text{ Hz} \cdot 2\sqrt{2.6}}$

$\boxed{a' = 3.8 \text{ cm}} = 0.038\text{m}$

$\boxed{a = 6.12 \text{ cm}} = 0.0612 \text{ m}$ w/ polystyrene

* Still need to see if b is important.

* NEXT BIG THING. Looking at Leakage.

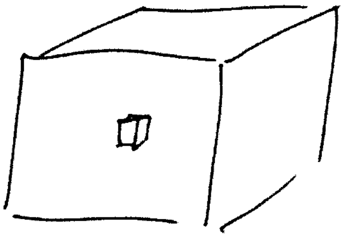
Stud. Mect. PAGE 3 FCS-3

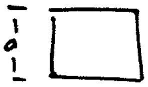
23/03/04

TE_{01}

$$\vec{E}_x = -C\,\frac{\pi}{b}\sin\left(\frac{\pi y}{b}\right)\exp i(\omega t - k_g z)$$

~~$\vec{E}_y = C\,\frac{b}{\pi}\cos\left(\frac{\pi y}{b}\right)\exp i(\omega t - k_g z)$~~





← our rectangular hole.

$$\boxed{0.001 < a < 0.0612\ \mathrm{m}} \rightarrow$$

$\lambda_c = 2a$

for microwaves

$a = 6.12\ \mathrm{cm} = 0.0612\ \mathrm{m}$

for infrared

$a = \frac{\lambda_c}{2} = 0.0005\mathrm{m}$

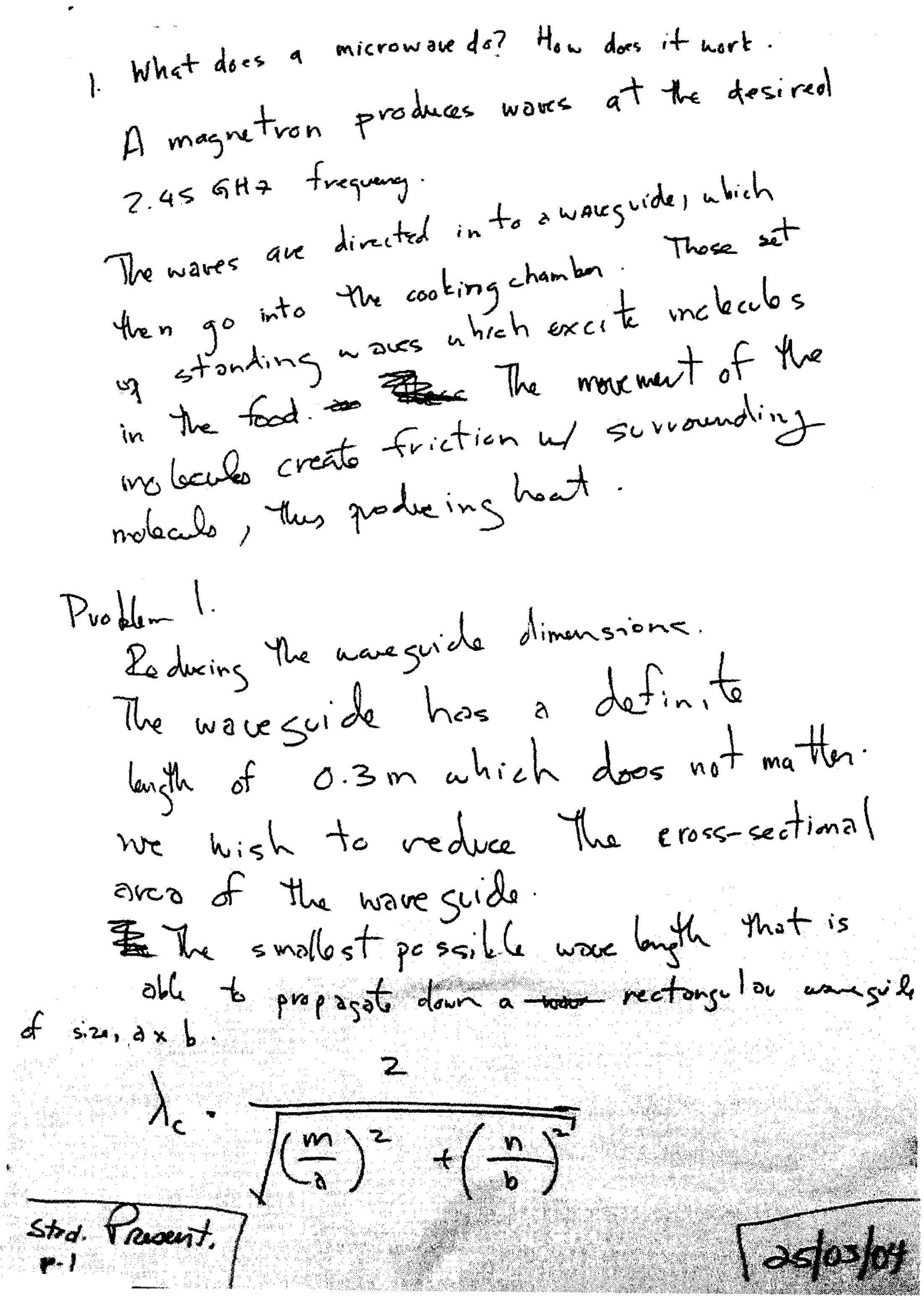
Session 2
Key 1
FC2-1

- max linear dimension
- Z
- ν of source.

Effective shielding for slots w/ dimensions $\leq \frac{\lambda}{2}$.

$$S = 20\log\left(\frac{\lambda}{2L}\right)$$

25/03/07



1. What does a microwave do? How does it work.

A magnetron produces waves at the desired 2.45 GHz frequency.

The waves are directed into a waveguide, which then go into the cooking chamber. Those set up standing waves which excite molecules in the food. The movement of the molecules create friction w/ surrounding molecules, thus producing heat.

Problem 1.

Reducing the waveguide dimensions.

The waveguide has a definite length of 0.3 m which does not matter.

We wish to reduce the cross-sectional area of the waveguide.

The smallest possible wavelength that is able to propagate down a rectangular waveguide of size, a x b.

$$\lambda_c \cdot \frac{2}{\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}}$$

Std. Present.
p-1

25/03/04

APPENDIX EEE: EXCERPT OF PBL SESSION 1 AND TUTORING CODING

(4 1 3) Hint	Tutor:	Don't we hope that the waves remain into microwaves?
	Stud3:	Yeah.
	Stud2:	Well if it didn't reflect then it would either heat up or not shield.
		Well it's not meant to heat up or let it through so it reflects...
	Stud3:	So let's look at...
	Stud2:	Otherwise it's not a shield right?
	*	((all laughing matter-of-factly))
	Stud3:	So so I'm still not too clear about these things...
(4 1 1) Question	Tutor:	What makes the walls absorb or reflect?
	Stud2:	But in a microwave it would be quite undesirable for the outer case if it just heated up really hot or not blocking waves.
(4 1 8) Evaluation	Tutor:	Yes that's quite right.
(4 1 1) Question		So you want it to ...
	Stud2:	Reflect.
(4 1 1) Question	Tutor:	What does it make?
(4 1 1) Question		What is it made of so it reflects the waves?
	Stud2:	Aluminium.
		So it is itself a waveguide.
	*	((Tutor providing scaffolding on reflecting walls of the
	*	cooking chamber and progressively leading to the discussion
	*	of shielding as a concept, including the role and properties
	*	of the door))
(4 1 5) Tell	Tutor:	So it reflects.
(4 1 3) Hint		Then how can you, how can you see into it?
	Stud2:	The glass.
	Stud4:	Yeah there is a glass...
	Stud3:	Hey wait a minute I don't know...
	*	((Stud-3 suddenly realizing that the glass might not
	*	be a shield by itself))
(4 1 5) Tell	Tutor:	So there's a glass.
(4 1 3) Hint		Does the glass reflect too?
	Stud3:	That's exactly what I'm wondering I just don't know...
	Stud2:	Well maybe it depends on the angle.
		If it were a completely normal incidence then maybe it wouldn't?
	Stud3:	You know this idea of total internal reflection?
		Well this only occurs if you have a margin...
	Stud2:	I'm not sure it's even relevant.
	Stud3:	No I mean I remember it occurs only if you're within a material that has a higher index of refraction and then you're going into a material that has less.
		Sort of you're in glass and you're going into air.
	Stud4:	Yeah.
	Stud3:	That's the only time you'll have it happen.
		I don't think you'll have it happen if it goes from air to glass.
	Stud2:	But what do you think happens?
	Stud3:	I'm not very clear on these ideas.
	*	((all laughing))

Stud4: None of us is.
Stud2: Maybe the microwaves are at such an angle with the glass that they get reflected.
(4 1 3) Hint Tutor: How can you control this angle with the microwaves bouncing off the sides?
Stud3: So what you're saying is…
* ((Stud-3 addressing Stud-2 directly))
Stud2: Well the microwaves don't get out of the microwave.
Stud3: Ok right.
Stud2: Although all the microwaves don't have glass.
Stud1: Well I don't think that a microwave needs glass.
Stud2: Yeah they can have only walls.
Stud1: Yeah I mean I don't know what would prefer the astronauts.
If they need to see?
Stud2: If it did have glass then you could use this infrared thermometer to look in there right?
Cause it's looking at the infrared radiations coming from it.
Stud1: Yeah.
Stud2: So if you had glass you wouldn't need a hole right?
Because that's how an infrared thermometer works.
(4 1 1) Question Tutor: Provided that…
Stud2: Provided that the heat waves don't get reflected inside the microwave.
(4 1 3) Hint Tutor: So the microwaves cannot get out but …
Stud4: The infrared can.
Stud1: That's cool.
Stud2: Then an infrared thermometer inside a microwave would also meet that condition.
Stud1: But we are not actually dealing with that situation…
Stud2: Yeah I know we're not doing the design of the thermometer…
So an infrared thermometer that works inside could also work outside the microwave as long as the infrared waves can get through.