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INQUIRY BASED LEARNING EXPERIENCES ON THERMAL PHENOMENA FROM SECONDARY SCHOOL TO UNIVERSITY: MOTIVATIONAL ASPECTS, CONCEPTUAL KNOWLEDGE AND NATURE OF SCIENCE VIEW

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Abstract

Scientific literacy is of increasing importance worldwide. Scientific information is used every day to make choices. People need to be able to engage intelligently in public debate about important issues involving science and technology. Creativity, particularly in design processes and data analysis, dynamism, flexibility and innovation are the mainly required professional qualities. Graduates should demonstrate to hold both specialist-discipline knowledge, abilities to solve practical problems, competences on using mathematical, scientific and technological tools to analyze and interpret data, communication skills and the mindset for undertaking lifelong learning. The development of all these competences needs an effective science and engineering instruction, which would be able to drive the students towards a deeper understanding of disciplinary fundamental concepts and, at the same time, to strengthen their reasoning skills and transversal abilities.

An effective learning of thermal science has always been a particularly arduous objective to be pursued, because of the difficulties, faced by students at any level of education, to understand everyday experiences governed by the intrinsic properties of matter. On the other hand, it is well established that learners' difficulties in problem solving may also be due to their views of science and/or inappropriate use of epistemological resources. It is widely recognized that both conceptual and epistemological difficulties on problem solving could be overcome by introducing the students to the practice of scientific reasoning and, in this view, a science education carried out by promoting the development of the process of *inquiry* – learning through questioning – has been long considered a viable solution. In fact, an inquiry-based teaching environment is today considered the natural framework where to develop opportunities for learning science in terms of an active construction of meaningful knowledge.

In this thesis, the results obtained through direct experimentation of two different kinds of inquiry-based physics learning path are reported and discussed. This study has been carried out with the aim to explore the benefits of a guided inquiry-based instruction of thermal science at secondary school and those coming from an open inquiry based learning experience at university. An introductory perspective on the theoretical framework of the Inquiry based Science Education (IBSE) is firstly provided. Subsequently, the two experimentations of inquiry based instruction, with different levels guidance (guided and open inquiry), are described. For each one of these, the teachers' perspectives and changes in their way of thinking about the adopted teaching methodologies are explored and discussed within the IBSE framework.

The first experimentation was carried out in the context of ESTABLISH, a FP7 European project aimed at promoting the development of IBSE in secondary schools. An extensive overview on the main objectives of the project, the general guidelines to unit development and a description of the implementation process of the inquiry-based science learning units, are provided. The overall purpose of this study was to explore the relationship between a guided

path of inquiry-based instruction on thermal science and the development of students' general ideas on science as a subject and usefulness of science and technology in everyday life. The research issues have been addressed by mean of ESTABLISH questionnaires, which were used to collect the opinions the students expressed about science and technology, by focusing on specific social aspects. The questionnaires also addressed those aspects of the Nature of Science (NOS) which are most commonly observed in students' discussions about science. A further research question addressed within the context of the ESTABLISH experimentation at secondary school has been focused on the efficacy of a guided inquiry (GI)-based teaching approach to motivate the students to learn science. Motivation plays a critical role in student learning and achievement, mainly because it is intimately related to the ways students think, feel, and act in schools.

The ESTABLISH experiences of GI-based learning produced an overall improvement of students' conceptions about the investigated NOS aspects. However, this result is barely noticeable in lower secondary students' answers, while a little more evident in upper secondary students' outcomes. Globally, our results suggest that secondary school students, engaged in inquiry-based guided experiences and without any specific instruction on NOS, experienced modest changes in their views on how scientific knowledge is produced and characterized, confirming what expressed in recent literature at this regard. On the contrary, significant results have been recognized in the context of motivational and social aspects of learning science through inquiry-based methods.

The second experimentation reported in this thesis is significant in that it is one of the first to explore quantitative relationships both between inquiry and conceptual learning as well as between inquiry and student epistemologies – beliefs students have about how scientific knowledge is produced. In this framework, we have addressed the problem of developing an effective – from the above-explained twofold point of view – strategy of instruction for science/engineering students, involved in the study of the physics underlying the complex world of thermal phenomena. We invited a group of engineering undergraduates, randomly selected among those who *already attended physics lectures*, to experience an Open Inquiry (OI) based learning environment. The students were involved in a high challenging project, aimed at the practical experimentation of ideas within a well defined research context, regarding the design of a thermodynamically efficient space base on Mars. By working in small groups, the students designed and carried out their own research activities, collected and analyzed data, shared their results.

Students' understanding of disciplinary concepts as well as processes of scientific reasoning connected with their epistemological beliefs on how to answer to science questions have been probed by using a questionnaire with common life open-ended problems on thermal science, which was administered prior to and after the OI-based instruction. Students' answers were classified into three epistemological profiles, characterized by different levels of ability to face and solve real-world problems by meaningfully applying the background of studied laws and theories. A pre-post-instruction comparative study was performed by means of statistical implicative analysis. We have found that engineering undergraduates, traditionally instructed, experience several difficulties on problem solving, due both to their epistemological stances and residual conceptual lacks. The OI-based activities performed by our students promoted their scientific reasoning, eliciting the meaning of the conceptual knowledge they already held. Within the theoretical framework of epistemological variability, these results suggest that an OI-based instructional environment may provide the students with appropriate cognitive resources to promote more productive epistemological stances, resulting in higher numbers of students solving problems successfully.

The scientific research reported in this thesis started from the need to explore new methods of teaching physics at school and university, based on putting the teaching strategy of scientific inquiry into practice. The science education community recognizes inquiry as a centrepiece of science teaching and learning, but many teachers are still striving to build a shared understanding of what science as inquiry means, and at the more practical level, what it looks like in the classroom. This topic has been explored in both the two experimentations described in this thesis.

Within the context of ESTABLISH, the teachers enrolled in the project were asked to answer a specific questionnaire concerning their usual teaching practice and their view of inquiry-based strategies of science instruction. The GI-based teaching path experienced by the teachers with their secondary school students actively involved in ESTABLISH had a positive effect on their perceptions of the potentialities of this teaching methodology.

Within the OI experimentation at university, a sample of upper secondary school physics teachers had the opportunity to personally experience an OI-based learning activity, with the aim of exploring the pedagogical potentialities of this teaching approach to promote both the understanding of difficult concepts and a deeper view of scientific practices. The teachers were firstly engaged in discussions concerning real life problematic situations, and then stimulated to design and carry out their own laboratory activities, aimed at investigating the process of energy exchange by thermal radiation. A structured interview conducted both before and after the OI experience allowed the author to analyze and point out the teachers' feedback from a pedagogical point of view. The advantages and limits of an OI-based approach to promote the development of more student-centred inquiry-oriented teaching strategies are finally discussed.

Dedicated to my family, Dominique, Emanuele and Gabriele

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Publications

Articles on ISI journals:

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2. **N. Pizzolato**, C. Fazio, O. R. Battaglia (2014), “Open Inquiry based learning experiences: a case study in the context of energy exchange by thermal radiation”, European Journal of Physics, 35, 015024.
3. **N. Pizzolato**, C. Fazio, R. M. Sperandeo Mineo, D. Persano Adorno (2014), “Open-inquiry driven overcoming of epistemological difficulties in engineering undergraduates: a case study in the context of thermal science”, Physical Review Special Topic – Physics Education Research, accepted for publication.

Proceedings:

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2. **N. Pizzolato**, O. R. Battaglia, C. Fazio, R. M. Sperandeo Mineo “Energy Exchange By Thermal Radiation: Hints and Suggestions for an Inquiry Based Lab Approach”. In: Twelfth International Symposium Frontiers of Fundamental Physics [FFP12], Udine, 21 November 2011.
3. **N. Pizzolato**, C. Fazio, R. M. Sperandeo Mineo, D. Persano Adorno, “Open Inquiry investigations on heat transfer performed by undergraduate engineering students”, World Conference on Physics Education. Istanbul, 1-6 July 2012.
4. **N. Pizzolato**, C. Fazio, R. M. Sperandeo Mineo, D. Persano Adorno, “Open Inquiry based learning experiences to understand the Nature of Science”, ICPE-EPEC International Conference on Physics Education, 5-9 August 2013, ISBN 978-80-7378-243-6.

Commonly used abbreviations

University of Palermo – UNIPA
Physics Education Research Group – PERG
Inquiry-Based Science Education – IBSE
Nature of Science – NOS
Organization for Economic Co-operation and Development – OECD
Program for International Student Assessment – PISA
Science and Technology in Action – STA
National Science Foundation – NSF
American Association for the Advancement of Science – AAAS
National Science Teachers Association – NSTA
Problem-Based Learning – PBL
National Science Education Standards – NSES
National Research Council – NRC
Experiential Learning Theory – ELT
No Child Left Behind – NCLB
Scientific Method – SM
Model-based Inquiry – MBI
Association for the Study of Higher Education – ASHE
Open Inquiry – OI
Guided Inquiry – GI
Lower secondary – LS
Upper Secondary – US
Pedagogical Content Knowledge – PCK
Industrial Content Knowledge – ICK

TABLE OF CONTENTS

CHAPTERS:

Chapter 1

Introduction

1.1 General framework and problem statement

In recent years, many studies have highlighted an alarming decline in young people's interest for key Science studies and Mathematics (Rocard et al., 2007; Osborne & Dillon, 2008), with the proportion of students progressing to University to study physical science across Europe firmly decreasing over the last decade (Education at a Glance, 2013). While the reasons for this decline are complex and multifaceted, there are indications that the decline in student interest in science starts in school (particularly in the early years of second level education), where there is a firm link between the student attitudes towards science and the way in which science is taught (Rocard et al., 2007; Osborne, 2003).

School education has to solve the problem of creating interest and a basic level of expertise for doing science as a career, on the one hand, and of stimulating interest and open-mindedness for dealing with science-based questions and decisions in daily life and in society, on the other hand (Report by the High Level Group on increasing Human Resources for Science and Technology in Europe, Europe needs more scientist, 2004; Rocard et al., 2007).

The report recently issued by the Organization for Economic Co-operation and Development (OECD) "Evolution of Student Interest in Science and Technology Studies" identifies the crucial role of positive contacts with science at an early stage in the subsequent formation of attitudes towards science (Global Science Forum, Encouraging student interest in science and technology studies, OECD, 2008). The studies show that one of the factors that influence the increase of interest, of motivation and of a positive attitude towards the study of sciences generally, and of physics particularly, is represented by the didactic methods used within the teaching-learning process. More than that, the attention must be focused on the teaching way during secondary school, which is the most important level in determining whether students prefer science studies, since it is at this stage that they can start choosing which subjects they wish to study.

The reasons for which new generations of students do not develop interest in science could be related to a lack of personal attitudes towards scientific thinking or due to the way scientific disciplines are proposed in schools or both. The increasing development of technology and its easy availability in our everyday life may have contributed to convince young people that they actually do not need to learn science, but just how to use technology. Moreover, despite the continuously increasing number of web-based resources should increase students' interest in science, the possibility to collect a great amount of information immediately available through the internet, has surely contributed to inform the students with the misleading view that everything in science is already known and easy to reach, reducing students' motivation towards the study of scientific disciplines.

This fact has to be viewed in conjunction with the general idea of scientific knowledge the teachers often transmit to the students, proposing a view of science as a list of unrelated concepts or facts, mainly based on the acquisition of knowledge mnemonically, rather than dedicated to a deep understanding of how the world works. This misleading approach guides the learners to develop the conception that science is a collection of scientific information. But students know that almost all information they need can be easily found on the web, and this may convince them of the uselessness to study science at school. Therefore, the pedagogical strategies the educators adopt to introduce physics concepts to their students represent a crucial aspect of the general problem of science learning at school or university.

First of all, students should clearly understand that scientific knowledge has nothing to do with memorizing facts, but they should be driven to develop a vision of science in terms of a challenging enterprise oriented towards the reasoned comprehension of how the world works. The impact of science in their everyday lives should be clearly introduced to the students since the beginning of their physics learning paths. The teachers should explain them the reasons beneath the need to know the rules – the physics laws – governing the natural phenomena. The students should understand that scientific knowledge is important to predict the evolution of dynamic systems, which are part of our everyday lives. They could be able to live a safer life by deeply understanding, for example, the functioning of the machines surrounding them. The study of physics should stimulate the students to develop comprehensive vision of science, not in terms of a stand-alone world made of complicated formulas, but as an explicatory model of the world itself. They should become aware of the usefulness of developing a scientific vision of the world. Moreover, the educators should clearly explain to their students that many aspects of the universe, from microscopic to macroscopic scales, are still unknown and a lot of natural phenomena, directly related to their everyday life, cannot be explained or predicted by the physics laws currently known. In this context, the teachers should describe to the students the work currently made by worldwide scientists, who carry out their activities with the aim to discover new laws or formulate theories explaining complex phenomena, and their methods of investigation. At last but not least, the social aspects of a given research activity should be always addressed and discussed with the learners. All the points discussed above are strictly connected to the need to provide the students with robust reasons to learn science. It is necessary to give students authentic experiences of science in school, increasing their interest and motivation in science. The achievement of high levels of motivation in students is perhaps the main challenge of physics education today.

At this respect, the teaching of physics in secondary schools has changed radically in the last decades. The old traditional method of instruction, even introducing the students to the main outcomes of famous physics experiments, was almost exclusively based on lectures aimed at transmitting theoretical concepts to the students. This system has been gradually replaced by methods taking into account the practice of experiments. However, this experimental part of students' instruction was initially carried out exclusively by the teachers, who maintained the central role of showing the experiment to their students. Only recently, by adopting a more constructivist view of science learning, teachers were more oriented to stimulate the students to directly experience the natural phenomena under investigation.

The Italian National Council of Public Education (DM n.9, 27.1.2010) has published a series of recommendations which promote the development of learning environments based on laboratory activities, suggesting to give more importance to the abilities that the students may develop with respect to specific contents. In this context, the acquisition of competences, as well as content knowledge, is warmly recommended by worldwide educational researches published in internationally recognized reports and papers on science education (Rocard et al., 2007; Osborne, 2003; Barrows & Wee Keng Neo, 2007; Duschl & Grandy, 2008; Pirrami, 2010) and it is also required by the most recent reorganization of secondary education and formally certified at the end of obligatory school (DPR n. 87, 5.3.2010). A first step towards the execution of these educational directives should include the development of annual programs starting from the analysis of the learning objectives, which have to be defined in terms of common skills among the experimental sciences and not on specific contents.

The crucial aspect is that the laboratory has not to be considered the place where students only observe experiences carried out by others or attend fruitless demonstrations of the validity of physics laws previously introduced by the teacher theoretically. The students must be personally involved in experimental activities, facing problematic situations that requires reasoning efforts, in order to be solved effectively. Moreover, the laboratory activity cannot be limited to the conduction of experiments and observations, but it should include a preliminary phase characterized by posing scientifically relevant questions, designing procedures and a final critical evaluation of obtained results. Furthermore, scientific practices also include the sharing of ideas with peers, drawing explicatory models, supporting conclusions and making choices based on arguments and evidences. All these activities constitute the core of Inquiry–based Science Education (IBSE), a teaching methodology that aims to promote the active participation of the students in the classroom through the use of scientific inquiry, towards a more direct understanding of "how" science effectively produces new knowledge. Inquiry is the “intentional process of diagnosing problems, critiquing experiments, and distinguishing alternatives, planning investigations, researching conjectures, searching for information, constructing models, debating with peers, and forming coherent arguments” (Linn et al. 2004).

The most recent results published from The Program for International Student Assessment (PISA) survey state that “mean performance in mathematics, reading and science is below the OECD average, but Italy is one of the countries that improved most markedly in both mathematics and science performance, particularly between 2006 and 2009”. In 2012, Italian students score 485 points, on average, in mathematics – comparable with Latvia, Lithuania, Norway, Portugal, the Russian Federation, the Slovak Republic, Spain and the United States. Italy’s mean performance improved between 2003 and 2012 by an average of 20 score points, moving substantially closer to the OECD average. Italy is one of the fastest improving countries in mathematics performance among those countries that participated in every PISA assessment since 2003. However, students in Italy tend to do better when the assessment covers their ability to interpret mathematical problems and situations (which requires students to apply and evaluate mathematical outcomes) and less well when the assessment covers their capacity to formulate situations mathematically.

The understanding of the experimental character of science can be facilitated if the student is stimulated to face and solve problems, by following the proper methods of scientific inquiry (Duit et al. 2005). Physicists face and solve a great amount of problems in their everyday research work and this mental efforts strengthen their reasoning skills and increase their ability to face unexpected situations. It should be considered that the understanding of how scientific knowledge is acquired, criticized and later reformulated, constitutes the basis for the development of scientific attitudes and critical thinking (Byrnea & Johnstone, 1987). It is widely recognized that both conceptual and epistemological difficulties on problem solving could be overcome by introducing the students to the practice of scientific reasoning and, in this view, a science education carried out by promoting the development of the process of *inquiry* – learning through questioning – has been long considered a viable solution (AAAS, 1993; NRC, 1996, 2000; Llewellyn, 2002). In fact, an inquiry-based teaching environment is today considered the natural framework where to develop opportunities for learning science in terms of an active construction of meaningful knowledge (Rocard et al., 2007; NRC, 2011; 2012).

Inquiry-based science education is considered to be an important current trend in science education reform (Rocard et al., 2007; NRC, 2012). In the European context, numerous inquiry-based science and mathematics projects[1] aim at promoting the development of inquiry-based science teaching methods and support the effective implementation of inquiry practices through the equally important contribution of both science content knowledge and pedagogical process knowledge (Rocard et al., 2007; Bolte, 2012). Very recent updates of the American standards of science education strongly encourage the development of instructional environments focused on the engagement in the practices of design, being convinced that this latter is equally important in the process of learning science, as the engagement in the practice of science (NRC, 2012; NAE & NRC, 2009).

The teaching strategies involved in inquiry approaches are grounded on the viewpoint that students are active thinkers, who construct their own understanding from interactions with phenomena, the environment, and other individuals. In inquiry-based learning, the students are engaged in identifying scientifically oriented questions, planning investigations, collecting

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[1] PROFILES (http://www.profiles-project.eu/); PATHWAY (http://www.pathway-project.eu/); PRIMAS (http://www.primas-project.eu/); FIBONACCI (http://www.fibonacci-project.eu/); ESTABLISH (http://www.establish-fp7.eu/) ; SAILS (http://www.sails-project.eu/).

data and evidences in laboratory and/or real life situations, building descriptions and explanation models, sharing their findings and eventually addressing new questions that arise. Depending on the amount of information and support provided by the teachers, the learners may be involved in a structured/guided inquiry (GI) or open inquiry (OI) (Schwab, 1962; Herron, 1971; Banchi & Bell, 2008). Generally, in structured inquiry the questions and procedures are provided by the teacher, and students generate their own explanations, supported by the evidence they have collected. In guided inquiry the teacher provides the students with only the research questions, and the students design the procedures to find reasonable answers and/or test the resulting explanations. In OI-based instruction, the teacher takes the delicate role of defining the context for inquiry, stimulating the students to derive their own questions, design and carry out independent investigations, construct coherent explanations, share their findings. This level of inquiry requires the highest capacity of scientific reasoning.

Many efforts have been carried out in order to introduce inquiry-based teaching approaches in K-12 grades of instruction (Mooney & Laubach, 2002; Crawford, 2007; Minner et al., 2010; Pyatt &.Sims, 2012; Redelman et al., 2012). A recent study (Lindsey et al., 2012) has shown positive shifts in the conceptual understanding and problem-solving categories of the Colorado Learning Attitudes about Science Survey (CLASS) by pre-service and in-service teachers experiencing the *Physics by Inquiry* curriculum (McDermott and the Physics Education Group at the University of Washington, 1996). At university level, the pedagogical effectiveness of incorporating guided inquiry-based activities, concerning the topic of heat transfer, has been observed in courses for chemical engineering undergraduates, who achieved higher overall scores on answering a post-instruction concept inventory (Nottis et al., 2010). Concerning the interaction between science concept learning and the using of inquiry activities, it is relevant to note that some researchers (Ogborn, 2012; Millar, 2012) although utterly convinced that physics education must include elements of real, genuine investigation for students to experience, show some criticism concerning two aspects about inquiry-based teaching approaches. The first one regards the impossibility of replicating the scientific process of inquiry in the frame of a typical science lesson (Ogborn, 2012). The second one is about the difficulty to use inquiry-based approaches to develop new scientific concepts (Millar, 2012). Some educational researchers consider the guided inquiry as the most appropriate approach for developing an effective understanding of critical concepts and also a deeper awareness of the nature of science (Lindsey et al., 2012), avoiding possible motivational effects that could be observed during OI and affect the successful completion of the learning process (Trautmann et al., 2004; Quintana et al., 2005).

Moreover, Berg et al. (2003) compared students' outcomes from an OI-based activity with those obtained in the context of a structured laboratory concerning the same experiment, finding the most positive results in students following the OI approach. Other studies assert that experiencing OI-based activities make possible to achieve higher levels of critical thinking skills and understanding the nature of science (Yen & Huang, 2001; Krystyniak & Heikkinen, 2007). Zion et al. (2004) conducted a long-term 3-year action research concerning the application of an OI approach to the study of biology. They considered the OI-based learning a dynamic process grounded on a continuous and renewed thinking activity, involving flexibility, judgment, and contemplation, as part of the changes that occur in the course of inquiry. In a subsequent paper, Sadeh and Zion (2009), compared the mean scores achieved by 12th grade students, experiencing guided inquiry, with those obtained by following an OI-based learning approach. They measured a significant difference between the scores achieved by the two groups. In particular, the OI outperformed guided inquiry in terms of "changes occurring during inquiry" and "procedural understanding", regarding affective aspects and the perspectives of critical and reflective thinking about the process.

In summary, an instruction based on structured/guided inquiry seems to be effective on repairing misconceptions (Nottis et al., 2010), but it is not yet clearly established its usefulness to produce functional epistemological perceptions of science (Chinn & Malhotra, 2002). On the other hand, students involved in OI learning experiences, having the purest opportunity to act like scientists, would gain the awareness of the process of scientific inquiry and a deeper view of the nature of science (Abd-El-Khalick, 2001; Schwartz et al., 2004; Flick, N. G. Lederman, 2006; Capps, B. A. Crawford, 2013). However, this latter approach, requiring the greatest cognitive demand from students in terms of scientific reasoning, may induce feelings of inadequacy or frustration, due, for example, to achieving of undesirable results, and could not bring about an effective understanding of the concepts (Trautmann et al., 2004; Quintana et al., 2005). It seems that both approaches, individually considered, could not result effective enough, suggesting to take into account integrated teaching/learning strategies.

Within this framework, many researchers have become increasingly interested in the interplay between science conceptual learning and other cognitive factors, such as personal learning frameworks (Pearsall et al., 1997), learning beliefs, and science epistemologies (Tsai, 1998, 1999; Hammer, 1994). It is relevant to note that when we talk about student epistemologies we are not talking about their broad general beliefs about the nature of science. Rather, we are referring to what Bing and Redish (2009) call functional epistemologies or personal epistemologies – i. e. "how students decide they know in a particular context in a particular moment" or how they decide what knowledge is relevant to bring to bear in solving a particular problem" or "what counts as valid proof". Here, we mainly analyze the influence of students' epistemological ideas on their approach to problem solving and the construction of their own scientific knowledge. It has been shown that students' epistemological beliefs about science play a significant role on their ability to solve a problem (Chi et al., 1981; Hofer, and P. R. Pintrich, 1997; Lising, and A. Elby, 2005; Bing & Redish, 2009). Novice learners usually consider scientific knowledge as a set of well-established theories and/or facts, supported by direct or indirect experimental validations. In students' naïve perceptions, the physics laws, being expressed in terms of mathematical equations and giving rise to the possibility of making precise predictions, are considered neither more nor less than computational tools for problem-solving (Schoenfeld, 1992; Redish et al., 1998). Students may achieve a distorted view of a physics law, considered exclusively as a mathematical entity to be applied within a specific problematic context, and completely miss its expression in terms of meaningful concepts (Tsai, 1999; Sandoval, 2005; Redish & Gupta, 2010). This epistemological stance is very strong and widespread, because it is grounded on the traditional view of science as a source of unfailing knowledge, capable of accurate quantitative expressions and rigorous methods of testing hypotheses.

Our guiding idea is that OI-based teaching strategies, promoting an involvement in activities similar to those carried out by scientists, should provide the students with the opportunity to deepen their understanding on how scientific knowledge is produced in real research contexts. Moreover, the way inquiry is implemented in the classroom has direct consequences upon the epistemological ideas that students might bring to bear on their work and on how the learning activity may change their perspective on scientific knowledge (Gupta et al., 2010). These “practical epistemologies” can be quite different from their perceptions of formal science and significantly affect the students’ ability to step forward on finding a solution to a problem.

In order to design an effective inquiry-based instruction, it is not sufficient to know what students know about a topic. One must consider the opportunity to produce a fruitful change on students’ epistemologies of science, which are not globally robust beliefs that drives students’ learning and problem-solving, but rather context-dependent locally-coherent views whose stability depends both on external inputs and on students’ internal conceptions and emotional states (White, and R. F. Gunstone, 1989; Vosniadou, 1994; Gupta, and A. Elby, 2011; Kuo et al., 2013).

However, IBSE requires a mind-set change on the part of the teacher away from a deductive approach where the teacher often presents the concepts and information, including results of experiments even before the student carries them out, to a more inductive approach where the teacher creates the atmosphere to allow for student observation, experimentation, planning, and through teacher guidance, students can construct their knowledge.

1.2 Rationale and research questions

A meaningful understanding of scientific concepts is achieved when the student is able to effectively face and solve common life problems requiring the practical application of those concepts. This is the reason of considering problem solving as a fundamental skill to develop and strengthen in young students and the most common way of evaluating the students’ understanding in physics. However, the training for developing problem solving skills is often carried out by asking the students to solve standard problems by using mathematical procedures mechanically. In this way, the students learn how to recognize the problem and connect it to another one, which has been previously solved with the learned procedure. This procedural knowledge has nothing to do with scientific knowledge, which is instead related to the development of reasoning abilities that allow a person to solve problems never encountered before.

The development of higher levels of abilities in problems solving, which essentially means the achievement of higher reasoning skills, is not an easy job to carry out. Some studies suggest that physics education through scientific inquiry can play a role in this context. But depending on the level of guidance provided by the educators to their pupils the efficacy of the teaching method may change significantly. A structured/guided inquiry seems more effective to target students' conceptual difficulties, but leaving almost unaffected their epistemological stances, which in some cases may result in a cognitive obstacle to a meaningful understanding of the concepts. On the other hand, an open inquiry method of instruction does not seem appropriate to introduce physics concepts to novice students, who often have no idea of how to proceed into a scientific exploration without a guide that explicitly tell them what to do, but it appears to be the most effective way for letting the students to discover and deeply understand the Nature of Science.

By summarizing, the main key-points are:

1. An effective knowledge of scientific concepts is achieved when the student is able to apply those concepts to solve problems never encountered before.
2. An appropriate training on problem solving, however, has to be based on the development and strengthening of students' reasoning skills.
3. Higher levels of thinking abilities can be achieved by "forcing" the students to personally experience the world and struggle for finding solutions to common life problems. This can be done by teaching the students to pose scientifically relevant questions, carry out scientific investigations, how to get significant measurements and analyse data, draw explanatory models, check results with further questions, share and discuss findings with peers.
4. This "forcing" can be obtained by involving the students in highly interesting learning projects and strongly motivating them to actively participate in the scientific endeavour. Inquiry-based teaching strategies should provide such highly motivating learning environment.
5. Teacher's role on providing a suitable scaffolding and/or guidelines is fundamental. At this regard, however, a greater student involvement with lower teacher guidance, such as in open inquiry learning environments, is recommended in order to achieve a deeper view of the nature of science. But some negative feelings, such as frustration due, for example, to run into mistakes or achieve unexpected results, could negatively affect the efficacy of the learning process.

In this context, the research questions addressed in this thesis are the following:

Guided-Inquiry (GI) at secondary school:

Experimental evidence: A GI-based teaching approach seems to be effective to achieve students' conceptual knowledge, but not useful to develop a deeper view of the Nature of Science, which is indeed necessary to overcome epistemological difficulties affecting their abilities on problem solving.

Unsolved problems: Lecture-based methods of science instruction at secondary school seem to provide only a merely factual knowledge, providing the students with the wrong (and boring) idea that science is a collections of unrelated facts. This approach cannot be considered a fruitful method of science instruction because:

- it provides a misleading view of science;
- it does not provide the motivation to an effective learning of science;
- it does not stimulate the strengthening of the students reasoning abilities.

Questions (addressed in the context of ESTABLISH):

1. Which basic ideas do secondary students have on school science and about the social impact of scientific knowledge on everyday life?
2. In what extent a GI-based teaching approach is suitable for achieving a change in students' perceptions of the nature of scientific knowledge?
3. Is the GI-based approach an effective teaching strategy to motivate students to learn science?
4. Which are the teachers' perceptions of GI-based teaching/learning pedagogies?

Open-Inquiry at university:

Experimental evidence: Traditionally-instructed undergraduates continue to experience difficulties on problem solving.

Unsolved problems: The origin of these difficulties on problem solving in already instructed students may be related to epistemology – their view of scientific knowledge – or to concepts – residual conceptual lacks – or both. En efficient strategy of instruction on problem solving, in terms of addressing both epistemological and conceptual issues, is still missing.

Questions (addressed in the context of thermal science):

1. Which are the main epistemological profiles of already instructed students on facing and solving common life problems in thermal science?

2. How effective is an OI-based learning environment to provide epistemological resources useful to help engineering undergraduates to improve their ability to solve problems on common life thermal phenomena?
3. How helpful is an OI-based learning environment to help already instructed engineering undergraduates to overcome residual conceptual difficulties on thermal science?
4. Which are the teachers perceptions of OI-based teaching/learning methodologies?

1.3 Research methods

Many different instruments and research methods have been used to collect and analyze the data reported in this thesis. In particular, both qualitative and quantitative research methods have been applied to this study. The experimentations of inquiry-based learning with students at secondary school and university were carried out in the presence of video recording systems that allowed to gather a huge amount of data. The students gladly accepted to be recorded only after the educators explained them that the videos would never be used for evaluating their activities in terms of assessment of knowledge of physics concepts and, for this reason, that they were completely free to enjoy their inquiry-based laboratory experience without any concern. The students were also asked to answer a questionnaire both prior to and after their performance of scientific inquiry activities.

The results reported in this thesis are mainly based on the analysis of questionnaire responses. In particular, the research questions concerning the GI-based experimentation have been addressed by mean of a closed-answer questionnaire, suitably developed and validated by the Irish team within the context of the ESTABLISH project. The questionnaire was aimed to collect information about the students' opinions on specific topics, such as "My Science Class", "Opinions about Science and Technology", assessing students' study practices and conceptions of learning and social nature of knowledge and their vision of the nature of science. Motivational aspects were also addressed.

The research carried out at university has been developed in different phases. Firstly, we constructed and validated an instrument having the form of an open-ended questionnaire, with the aim of collecting information about the typical difficulties encountered by young undergraduates. Students' understanding of disciplinary concepts as well as processes of scientific reasoning connected with their epistemological beliefs on how to answer to science questions have been probed by using a questionnaire with common life open-ended problems on thermal science, which was administered prior to and after the OI-based instruction. Students' answers were classified into three epistemological profiles, characterized by different levels of ability to face and solve real-world problems by meaningfully applying the background of studied laws and theories. The construction of analytical categories was based on a careful reading of the students' answers by the authors, by using the framework provided by domain-specific expertise and a phenomenographic approach (Marton, 1988; Marton & Booth, 1997; Richardson, 1999). A pre-post-instruction comparative study was performed by means of statistical implicative analysis (Gras et al., 2008), in order to quantitatively estimate both similarities and implications between different students' answering strategies.

Finally, the evaluation of teachers practices and attitudes in the context of both GI and OI based pedagogical approaches has been performed by mean of questionnaires and targeted interviews.

Chapter 2

Theoretical framework

2.1 Constructivist Theory and the birth of Inquiry-based pedagogies

A complete discussion about the theory of constructivism would need a very extensive treatment which goes beyond the purpose for which this section was thought. Here we want to summarize the key concepts of a learning theory, based on observation and scientific studies, which is grounded on the basic idea that learners construct knowledge by themselves.

The first concept is that *people construct their own understanding of the world*, through experiencing things and reflecting on those experiences. This process brings each learner to construct a meaning of what he experiences and the construction of meaning is learning. When we encounter something new, we have to conciliate it with our previous ideas and experience, maybe by including the new information in our body of knowledge, or maybe discarding it as irrelevant. In any case, we are principal actors of the process of learning and the way we perform this process is by asking questions, exploring, and continuously assessing our previously supported beliefs.

The process of inquiring begins with gathering information and data through applying the human senses - seeing, hearing, touching, tasting, and smelling. Infants begin to make sense of the world by *inquiring*; people carry on the process of inquiry from the time they are born until they die, even though they might not be conscious that they are learning.

At the beginning of the last century, the fundamental role of experience on education was emphasized by the American philosopher and psychologist John Dewey (1902, 1916, 1938). At that time, the authoritarian approach of traditional education was too concerned with delivering knowledge, and not enough with understanding students' actual experiences, with the traditional curriculum undoubtedly entailing a rigid discipline that ignored the capacities of the individual learner. But the reaction to that type of schooling, however, was often characterized by the fostering of excessive individualism and spontaneity. Dewey was critical with respect to a completely "free, student-driven" education because “students often don't know how to structure their own learning experiences for maximum benefit”. Dewey pointed out that neither the old nor the new system of education was adequate, because neither of them applied the principles of a carefully developed *philosophy of experience*.

In Dewey’s theory, education is considered as the scientific method by means of which men investigate the world, acquire cumulatively knowledge of those meanings and values, which will constitute the fundamental bases for the development of a critical study and intelligent living. Dewey advocated for an educational structure that strikes a balance between delivering knowledge while also taking into account the interests and experiences of the student. However, the experience is educative only to the degree that it rests upon a continuity of significant knowledge and to the degree that this knowledge modifies the learner's outlook, attitude, and skill.

Dewey is one of the most famous proponents of hands-on learning or experiential education, which is related to the concept of experiential learning. He argued that:

> "*if knowledge comes from the impressions made upon us by natural objects, it is impossible to procure knowledge without the use of objects which impress the mind*" (Democracy and Education,1916, p. 217-218).

Experiential learning occurs when carefully chosen experiences are supported by reflection, critical analysis and synthesis. Throughout the experiential learning process, the learner is actively engaged in posing questions, investigating, experimenting, being curious, solving problems, assuming responsibility, being creative, and constructing meaning. Within this context, the educator's primary roles include setting suitable experiences, posing problems, setting boundaries, supporting learners, insuring physical and emotional safety, and facilitating the learning process. Experiences are structured to require the learner to take initiative, make decisions and be accountable for results. The design of the learning experience includes the possibility to learn from natural consequences, mistakes and successes.

The concept of *effective learning* which brings about a significant knowledge of the world, even if stated by Dewey almost one hundred years ago, appears to be strongly alive still nowadays. Students should be involved in a learning environment where they are allowed to experience and interact with the curriculum and have the opportunity to take active part in their own learning.

The Italian educator Maria Montessori (1912) contributed to both Humanism and Constructivism. The so called “Montessori method”, which is still implemented today, is a child-centred, alternative educational method based on the child development theories proposed by Maria Montessori in the late 19th and early 20th centuries. Primarily applied in pre-school and primary (elementary) school settings (and occasionally in infant, toddler, middle school, and high school), this method of education is characterized by emphasizing self-directed activity on the part of the child, and clinical observation on the part of the teacher to stress the importance of adapting the child’s learning environment to his or her development level, and the role of physical activity in the child’s absorbing abstract concepts and learning practical skills. The following quote from her emphasizes her value of experiential learning to condition knowledge:

> "*Scientific observation has established that education is not what the teacher gives; education is a natural process spontaneously carried out by the human individual, and is acquired not by listening to words but by experiences upon the environment.*”
>
> “*When St. Francis of Assisi saw his Lord in a vision, and received from the Divine lips the command–"Francis, rebuild my Church!"–he believed that the Master spoke of the little church within which he knelt at that moment. And he immediately set about the*

> *task, carrying upon his shoulders the stones with which he meant to rebuild the fallen walls. It was not until later that he became aware of the fact that his mission was to renew the Catholic Church through the spirit of poverty. But the St. Francis who so ingenuously carried the stones, and the great reformer who so miraculously led the people to a triumph of the spirit, are one and the same person in different stages of development. So we, who work toward one great end, are members of one and the same body; and those who come after us will reach the goal only because there were those who believed and laboured before them. And, like St. Francis, we have believed that by carrying the hard and barren stones of the experimental laboratory to the old and crumbling walls of the school, we might rebuild it.*"

Jean Piaget was very interested in knowledge and how children come to know their world (Piaget, 1928). He developed his cognitive theory by actually observing children, some of whom were his own children, demonstrating empirically that children's minds actively process the material with which they are presented (Piaget, 1952, 1954). Using a standard set of questions as a starting point, he followed the child's train of thought and observed how the child constantly interacts with the world around him, developing a more flexible questioning and allowing the invention and reinvention of knowledge. Piaget believed that the process of thinking and the intellectual development could be regarded as an extension of the biological process of the evolutionary adaptation of the species, which has also two on-going processes: assimilation and accommodation (Piaget, 1971). According to Piaget, children use the process of assimilation and accommodation to create a schema or mental framework for how they perceive and/or interpret what they are experiencing. Assimilation is when a child responds to a new event in a way that is consistent with an existing schema, while accommodation is when a child either modifies an existing schema or forms an entirely new schema to deal with a new object or event. Intelligence grows through the twin processes of assimilation and accommodation; therefore, experiences should be planned to allow opportunities for assimilation and accommodation. A Piagetian-inspired curricula emphasizes a learner-centred educational philosophy. Children need to explore, to manipulate, to experiment, to question, and to search out answers for themselves - activity is essential. However, this does not mean that children should be allowed to do whatever they want. So what is the role of the teacher? Teachers should be able to assess the child's present cognitive level; their strengths and weaknesses. Instruction should be individualized as much as possible and children should have opportunities to communicate with one another, to argue and debate issues. Piaget saw teachers as facilitators of knowledge - they are there to guide and stimulate the students. Learning is much more meaningful if the child is allowed to experiment on his own rather than listening to the teacher lecture. The teacher should present students with materials and situations and occasions that allow them to discover new learning.

David A. Kolb, in his books Learning Style Inventory and Learning Style Inventory: Technical Manual (1976), emphasizes the importance of conditioned knowledge through experiential learning. In the early 1970s, David A. Kolb and Roger Fry (1975) developed the Kolb & Fry (Experiential Learning) Model, which was characterized by the following four elements: concrete experience, observation and reflection, the formation of abstract concepts, and testing in new situations.

The Experiential Learning Theory (ELT) draws on the work of prominent twentieth century scholars who gave experience a central role in their theories of human learning and development - notably John Dewey, Kurt Lewin, Jean Piaget, William James, Carl Jung, Paulo Freire, Carl Rogers, and others – with the aim of developing a holistic model of the experiential learning process and a multi-linear model of adult development. The theory, described in the Kolb's work *Experiential Learning: Experience as the Source of Learning and Development* (1984), is built on six propositions that are shared by these scholars:

1. Learning is best conceived as a process, not in terms of outcomes. To improve learning in higher education, the primary focus should be on engaging students in a process that best enhances their learning — a process that includes feedback on the effectiveness of their learning efforts. "...education must be conceived as a continuing reconstruction of experience: ... the process and goal of education are one and the same thing." (Dewey 1897: 79).
2. Learning is best facilitated by a process that draws out the students' beliefs and ideas about a topic so that they can be examined, tested, and integrated with new, more refined ideas.
3. Learning requires the resolution of conflicts between dialectically opposed modes of adaptation to the world. Conflict, differences, and disagreement are what drive the learning process, in which the learner is called upon to move back and forth between opposing modes of reflection and action and feeling and thinking.
4. Learning is a holistic process of adaptation to the world. It is not just the result of cognition but involves the integrated functioning of the total person — thinking, feeling, perceiving, and behaving.
5. Learning is the process of creating knowledge. In Piaget's terms, learning occurs through equilibration of the dialectic processes of assimilating new experiences into existing concepts and accommodating existing concepts to new experience. ELT proposes a constructivist theory of learning whereby social knowledge is created and recreated in the personal knowledge of the learner. This stands in contrast to the "transmission" model on which much current educational practice is based, where pre-existing fixed ideas are transmitted to the learner.

Experiential learning is a process of constructing knowledge that involves a creative tension among the four learning modes that is responsive to contextual demands. This process is portrayed as an idealized learning cycle or spiral where the learner “touches all the bases” — experiencing, reflecting, thinking, and acting-in a recursive process that is responsive to the learning situation and what is being learned (Figure 2.1).

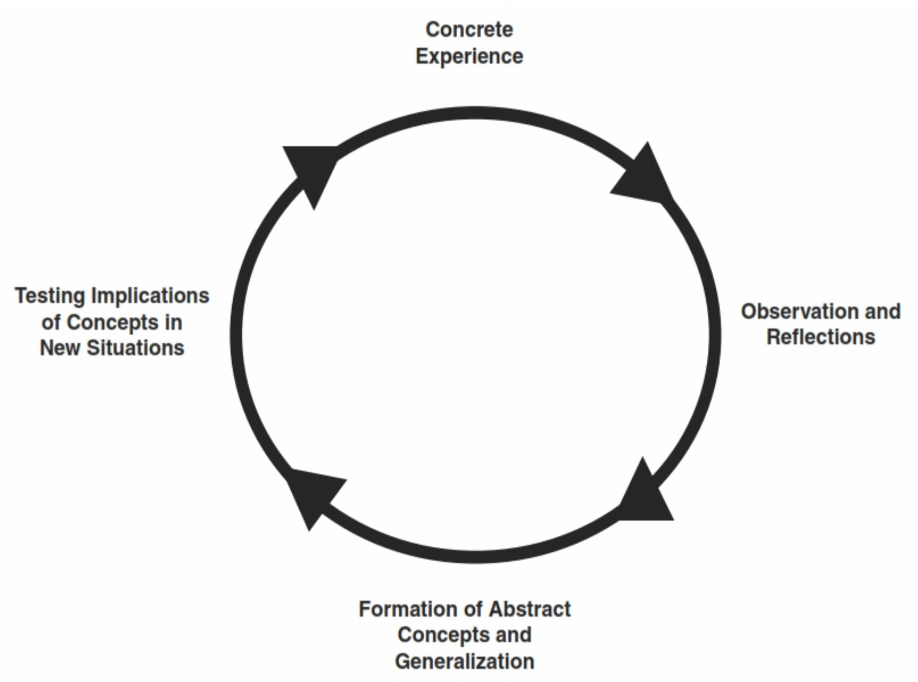


Figure 2.1 The Experiential Learning Cycle.

There is no knowledge independent of the meaning attributed to the experience constructed by the learner, or community of learners. However, it should be clearly stated that the crucial action of constructing meaning is mental: it happens in the mind. Physical actions, hands-on experience may be necessary for learning, especially for children, but it is not sufficient; we need to provide activities which engage the mind as well as the hands. Dewey called this *reflective activity*. In the classroom, the constructivist view of learning can point towards a number of different teaching practices. In the most general sense, it usually means encouraging students to use active techniques (experiments, real-world problem solving) to create more knowledge and then to reflect on and talk about what they are doing and how their understanding is changing. The teacher makes sure she understands the students' preexisting conceptions, and guides the activity to address them and then build on them. Constructivist teachers encourage students to constantly assess how the activity is helping them gain understanding. By questioning themselves and their strategies, students in the constructivist classroom ideally become "expert learners." This gives them ever-broadening tools to keep learning. With a well-planned classroom environment, the students learn “how to learn”.

The constructivist position argues that knowledge is not transmitted directly from one person to another but must be actively built by the learner. This means that teachers have to focus on the learner, as an active maker of meanings, in thinking about learning and not on the subject/lesson to be taught; the role of the teacher is to enter into a dialogue with the learner. Traditionally, the teacher takes care of a major part of all higher cognitive functions at school, such as planning, questioning, explaining and evaluating, while the students are required to understand, restore and reproduce transmitted information. Based on cognitive studies of expertise, Bereiter and Scardamalia (1989) have proposed that an important prerequisite for development of higher-level cognitive competencies is that students themselves take on a responsibility for all cognitive (e.g., questioning, explaining) and metacognitive (e.g., goal-setting, monitoring, and evaluating) aspects of inquiry.

In the study of cognition performed by Jerome Bruner (1956), the learner selects and transforms information, constructs hypotheses, and makes decisions, relying on *cognitive structures* (i.e., schema, mental models), which provides meaning and organization to experiences and allows the individual to "go beyond the information given". The instructor should try and encourage students to discover principles by themselves. The instructor and student should engage in an active dialog (i.e., Socratic learning). The task of the instructor is to translate information to be learned into a format appropriate to the learner's current state of understanding.

Cognitive analyses of science learning and reasoning have provided many important insights into the development of curricula and methods in science and mathematics (e.g., Bruer, 1994; Bransford, Brown, & Cocking, 1999). Cognitive analyses of science students' content knowledge, for example, have provided new insights into how students' alternative conceptions differ from scientific conceptions, and thus into how conceptual change topics can be taught more effectively (e.g., Driver et al., 1994). Furthermore, cognitive analyses have provided insights into how to promote conceptual change (e.g., Smith et al., 1992; Guzzetti et al., 1993; Driver et al., 1994) and how to promote epistemological development (e.g., Carey et al., 1989; diSessa, 1993; Smith et al., 2000).

Finally, it should be emphasized that *learning is a social activity*. Our learning is intimately associated with our connection with other human beings, our teachers, our family as well as casual acquaintances. We can distinguish between "cognitive constructivism", which is about how the individual learner understands things, in terms of developmental stages and learning styles, and "social constructivism", which emphasizes how meanings and understandings grow out of social encounters. Much of traditional education, as Dewey pointed out, is directed towards isolating the learner from all social interaction. In contrast, progressive education (to continue to use Dewey's formulation) recognizes the social aspect of learning and uses conversation, interaction with others. Vygotskij proposed a theory of the development of higher cognitive functions in children that saw the emergence of the reasoning as emerging through practical activity in a social environment. For Vygotskij, the zone of proximal development, that is

> ". . . *the distance between the actual development of a child as determined by the independent problem solving, and the level of potential development as determined through*

> *problem solving under adult guidance or in collaboration with more peers*“ (Vygotskij, 1978, p86)

suggests that cognitive development is limited to a certain range at a particular age. However, with the help of social interaction, such as assistance from a mentor, students can comprehend concepts and schemes that they cannot know on their own. In other words, through the assistance of a more capable person, a child is able to learn skills or aspects of a skill that go beyond the child’s actual developmental or maturational level. Therefore, development always follows the child’s potential to learn.

Scaffolding is a concept closely related to the idea of zone of proximal development, although Vygotskij never actually used the term. Scaffolding is a dynamic process of changing the level of support to suit the cognitive potential of the child. Over the course of a teaching session, a more skilled person adjusts the amount of guidance to fit the child’s potential level of performance. More support is offered when a child is having difficulty with a particular task and, over time, less support is provided as the child makes gains on the task. A Vygotskian classroom emphasizes creating one’s own concepts and making knowledge one’s property; this requires that school learning takes place in a meaningful context, alongside the learning that occurs in the real world. This model promotes the active participation and collaboration of distinctive learners and stresses assisted discovery through teacher-student and student-student interaction. Some of the cognitive strategies that group members bring into the classroom are questioning, predicting, summarizing, and clarifying, which are all typical of inquiry processes.

In summary, education and learning are social and interactive processes, and thus the school itself is a social institution through which social reform can and should take place. The purpose of education should not revolve around the acquisition of a pre-determined set of skills, but rather the strengthening of the ability to use those skills for greater engagements in the society. Scientific inquiry has not to be view as an individual performance but a socially distributed process both in science and in learning (see Oatley, 1990; Hutchins, 1991; Zhang & Norman, 1994). Limitations of human information processing can be overcome by relying on socio-culturally developed cognitive tools, artifacts, and good cognitive practices. All aspects of inquiry, such as generation of research questions, search for explanatory scientific information or construction of one’s own theory, can be shared with other inquirers. Cognitive research indicates that advancement of inquiry can be substantially elicited by relying on socially distributed cognitive resources, emerging through social interaction between the learners, and collaborative efforts to advance shared understanding.

2.2 Project 2061 and the National Science Education Standards: A Guide for Teaching and Learning

From the beginning of the XX century up to sixties, the system of science education has certainly changed under the renewal pulse inspired by constructivist ideas of learning. In the United States the plans to reorganize science were based on the works of The Committee of Ten (1893), the Commission on Reorganization of Secondary Education (1918), the National Science Foundation (NSF) grants and National Defense Education Act (1950s). The NSF was one of the primary forces shaping the science reforms of the 1950's and 60's, but the changing was oriented more towards the reform of the content of curricula with respect to organize a real improvement of teaching/learning methodologies.

In 1985 the American Association for the Advancement of Science (AAAS) founded *Project 2061*, *Education for a changing future*, to help all Americans to become literate in science, mathematics, and technology. Children who were just starting school in 1989 - the year Halley's Comet passed near Earth - will probably see the return of the comet in 2061. The driving questions were: “What scientific and technological changes will they also see in their lifetime? How can today's education prepare them to make sense of how the world works; to think critically and independently; and to lead interesting, responsible, and productive lives in a culture increasingly shaped by science and technology?”

In 1991, the National Science Teachers Association (NSTA) asked the National Research Council (NRC) to develop standards for science education. Between 1991 and 1995, groups of teachers, scientists, administrators, teacher educators, and others organized by the NRC produced several drafts of the standards and submitted those drafts to extensive review by others in these same roles. Major reform documents in science education, such as *Science for All Americans* (Rutherford & Ahlgren, 1991) from Project 2061 of the AAAS and National Science Education Standards (NSES) from the NRC (1996), have stressed the need for a scientifically literate populace. *Project 2061* set out to identify what was most important for the next generation to know and be able to do in science, mathematics, and technology. The publication Science for All Americans defines science literacy and lays out some principles for effective learning and teaching in the following areas:

- The Nature of Science includes the scientific world view, scientific methods of inquiry, and the nature of the scientific enterprise.
- The Nature of Mathematics describes the creative processes involved in both theoretical and applied mathematics.
- The Nature of Technology examines how technology extends our abilities to change the world.
- The Physical Setting lays out basic ideas about the content and structure of the universe and the physical principles on which it seems to run.

- The Living Environment delineates basic facts and ideas about how living things function and how they interact with one another and their environment.
- The Human Organism discusses human biology as exemplary of biological systems.
- Human Society considers individual and group behavior, social organizations, and the process of social change.
- The Designed World reviews principles of how people shape and control the world through some key areas of technology.
- The Mathematical World gives basic mathematical ideas, especially those with practical application, that together play a key role in almost all human endeavours.
- Historical Perspectives illustrates the science enterprise with ten examples of exceptional significance in the development of science.
- Common Themes presents general concepts, such as systems and models, that cut across science, mathematics, and technology.
- Habits of Mind sketches the attitudes, skills, and ways of thinking that are essential to science literacy.

The NSES present a vision of a scientifically literate populace. They outline what students need to know, understand, and be able to do to be scientifically literate at different grade levels. They describe an educational system in which all students may demonstrate high levels of performance, in which teachers are empowered to make the decisions essential for effective learning, in which interlocking communities of teachers and students are focused on learning science, and in which supportive educational programs and systems nurture achievement. The Standards were designed to be applied to all students, regardless of age, gender, cultural or ethnic background, disabilities, aspirations, or interest and motivation in science. Different students could achieve understanding in different ways, or different degrees of depth and breadth of understanding, depending on interest, ability, and context. But all students should be stimulated to develop the knowledge and skills described in the standards, even as some students could be able to go well beyond these levels.

The standards rest on the premise that science is an active process. Learning science is something that students do, not something that is done to them. "Hands-on" activities, while essential, are not enough. Students must have "minds-on" experiences as well. The standards call for more than "science as process," in which students learn such skills as observing, inferring, and experimenting. Inquiry is a central theme in the NSES and its clarifying documents (NRC, 2000) as well as in significant international reform documents (Tomorrow 98 Report, 1992; Australian Education Council, 1994). When engaging in inquiry, students describe objects and events, ask questions, construct explanations, test those explanations against current scientific knowledge, and communicate their ideas to others. They identify their assumptions, use critical and logical thinking, and consider alternative explanations. In this way, students actively develop their understanding of science by combining scientific knowledge with reasoning and thinking skills. Just as inquiry has many different facets, so teachers need to use many different strategies to develop the understandings and abilities described in the standards.

In June 1999, the first World Conference on Science held in Budapest and sponsored by, among others, UNESCO, recognised “an urgent need to renew, expand and diversify basic science education for all”. The conference declaration viewed the following as commitments and requirements for science and cultural organisations over the world: “Science education, in the broad sense, without discrimination and encompassing all levels and modalities, is a fundamental prerequisite for democracy and for ensuring sustainable development. In recent years, worldwide measures have been undertaken to promote basic education for all … Special attention still needs to be given to marginalized groups. It is more than ever necessary to develop and expand science literacy in all cultures and all sectors of society as well as reasoning ability and skills and a appreciation of ethical values, so as to improve public participation in decision-making related to the application of new knowledge”.

National academies in Europe have a strong and long-standing commitment to promoting science literacy and formal and informal science education in their countries, often with the help of European Union co-funded programmes, and in alliance with educational authorities and influential partners in the corporate sector. For instance, on 4 December 2003 a statement on “Science Education of Children” was issued at an Inter-Academy Plenary meeting in Mexico City and was signed by 29 European science academies, with working groups having a strong focus on IBSE.

In the wake of the NSES, the European Commission clearly defines the central role of Inquiry to science learning in the document entitled *Science Education NOW: A Renewed Pedagogy for the Future of Europe* (2007). When engaging in inquiry, students describe objects and events, ask questions, construct explanations, test those explanations against current scientific knowledge, and communicate their ideas to others. They identify their assumptions, use critical and logical thinking, and consider alternative explanations. In this way, students actively develop their understanding of science by combining scientific knowledge with reasoning and thinking skills (Osborne & Dillon, 2008).

More recently, the National Research Council’s (NRC) has published the document *Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (2011), developing a guiding framework to standardize K-12 science education, with the goal of organizing science education systematically across the K-12 years. The NRC publication emphasizes science educators to focus on a "limited number of disciplinary core ideas and crosscutting concepts, be designed so that students continually build on and revise their knowledge and abilities over multiple years, and support the integration of such knowledge and abilities with the practices needed to engage in scientific inquiry and engineering design."

In 2013 new standards for science education were released that update the national standards released in 1996. Developed by 26 state governments and national organizations of scientists and science teachers, the guidelines, called the *Next Generation Science Standards*, are intended to "combat widespread scientific ignorance, to standardize teaching among states, and to raise the number of high school graduates who choose scientific and technical majors in college....". Included are guidelines for teaching students about topics such as climate change and evolution. An emphasis is teaching the scientific process so that students have a better understanding of the methods of science and can critically evaluate scientific evidence.

For the most part, these reform initiatives have recommended an inquiry-based approach to science education, real-world problem solving for students, the use of cooperative learning strategies, a focus on content depth rather than breadth, and teachers as facilitators of learning rather than deliverers of information (Moreno, 1999). While constructivism is often viewed from either cognitive (within the individual) or socio-cultural (within a community of learners) perspectives (Cobb, 1994), science learning can be seen to entail both personal and social processes (Driver et al., 1994). As a result, most calls for reform in science education emphasize engaging students in inquiry to promote active development of understanding by individuals, and having students collaborate while learning to promote communication and the development of shared meaning. In order to help students apply what they learn to real-world situations, it is argued that learning should be situated in authentic activity (Brown, Collins, & Duguid, 1989) such as real-world problem solving (Savery & Duffy, 1996). Technology is often mentioned as an important element of science education reform efforts because it is seen as a unique agent that can anchor students' learning and/or support or augment the construction of meaning (Cognition and Technology Group at Vanderbilt, 1997).

Despite the worldwide community of science educators perfectly agrees with the standards and it is firmly convinced of their efficacy to promote an active participations of the learners and to build a globally interconnected scientific literacy, in the United States only 12% of high school science teachers in the Hudson et al. (2002) survey said that they had implemented recommendations from the NSES in their science teaching and only 4% strongly agreed with the statement ''I am prepared to explain the NSES to my colleagues.'' The infrequency of inquiry-based teaching found in these large-scale surveys and interviews is consistent with the findings of studies from the full range of research traditions (Abd-El-Khalick et al., 2004; Crawford, 2007), as well as data collected in countries other than the United States (Osborne & Dillon, 2008).

Many barriers to implementing inquiry in a manner consistent with the vision of the NSES have been described in the literature (Lederman & Lederman, 2004; Crawford, 2007). Anderson (2002) categorizes these as political dilemmas (such as parental resistance and conflicts between teachers), cultural dilemmas (such as differing beliefs and values about learning and assessment), and technical dilemmas (which include limited abilities to teach and assess). Similarly, Tobin and McRobbie (1996) described a series of cultural beliefs about teaching and learning that constrain teachers' pedagogical moves and result in teaching practices discordant with teaching science as inquiry (Lotter, Harwood, & Bonner, 2007).

The No Child Left Behind (NCLB) legislation (U.S. Department of Education, 2002) and the associated accountability movement (OCSE-PISA) have led to an increased emphasis on standardized testing to measure teacher and school effectiveness. In turn, some have argued (see e.g., Blanchard, Annetta, & Southerland, 2008) that standardized testing (i) has resulted in teaching practices that are at odds with those advocated in the national science education reform documents (AAAS, 1993, 2000; NRC, 1996, 2000), (ii) has had negative effects on science teachers' perceptions of the quality of their teaching (Shaver, Cuevas, Lee, & Avalos, 2007), and (iii) has created pressures for teachers to prepare students for tests that cover large amounts of content and emphasize factual knowledge (Whitford & Jones, 2000). NCLB and the current climate in the rest of the world therefore present one further obstacle to inquiry's role in reform: accountability and inquiry-based teaching can appear incompatible to teachers (Blanchard et al., 2008).

2.3 Inquiry-based Learning and the 5E Model

In this section we would like to explicitly describe the specifics of IBSE. From a cognitive point of view, inquiry can be characterized as a question driven process of understanding. Without a research question there cannot be a genuine process of inquiry, although information is frequently produced at school without any guiding questions. A research question activates an agent's background knowledge by facilitating in-depth search of memory and focusing memory search in a specific direction; simultaneously, it facilitates making inferences from one's knowledge through parallel activation of different beliefs; it guides one continuously to relate what he or she already knows to new information (Scardamalia & Bereiter, 1992). The question-driven process of inquiry provides heuristic guidance in the search for new scientific information. Considerable advancement of inquiry cannot be made without obtaining new information. Indeed, all scientific information does not have equal cognitive value; explanatory or theoretical knowledge has a key role in conceptual understanding, and, thus, a special status in the cognitive process of inquiry.

Teaching science through inquiry allows students to conceptualize a question and then seek possible explanations that respond to that question. Students need to learn the principles and concepts of science, acquire the reasoning and procedural skills of scientists, and understand the nature of science as a particular form of human endeavour. Students therefore need to be able to devise and carry out investigations that test their ideas, and they need to understand why such investigations are uniquely powerful. Studies show that students are much more likely to understand and retain the concepts that they have learned this way. For example, one skill that all students should acquire through their science education is the ability to conduct an investigation where they keep everything else constant while changing a single variable. This ability provides a powerful general strategy for solving many problems encountered in the workplace and in everyday life. The challenge for all of us who want to improve education is to create an educational system that exploits the natural curiosity of children, so that they maintain their motivation for learning not only during their school years but throughout life.

Another important aspect of inquiry is generation of one's own explanations, hypotheses or conjectures (Scardamalia & Bereiter, 1992; Carey & Smith, 1993). In order to foster dynamic change of conceptions and integration of knowledge structures, an agent has to engage in an intentional process of generating his or her own explanations and theories. If the process of inquiry is carried out as a strong, systematic cognitive effort and relevant new information is obtained, the agent often succeeds in creating more and more sophisticated explanations. Knowledge emerges through his or her intentional attempts to explain and understand problems being investigated; it is usually connected with the learner's other knowledge in a rich web of meaning connections.

Heather Banchi and Randy Bell (2008) suggest that there are four levels of inquiry-based learning in science education:

1. *Confirmation inquiry*: students are provided with the question and procedure (method), and the results are known in advance. Confirmation inquiry is useful when a teacher's goal is to reinforce a previously introduced idea; to introduce students to the experience of conducting investigations; or to have students practice a specific inquiry skill, such as collecting and recording data;
2. *Structured inquiry*: the question and procedure are still provided by the teacher; however, students generate an explanation supported by the evidence they have collected;
3. *Guided inquiry*: the teacher provides students with only the research question, and students design the procedure (method) to test their question and the resulting explanations. Because this kind of inquiry is more involved than structured inquiry, it is most successful when students have had numerous opportunities to learn and practice different ways to plan experiments and record data;
4. *Open inquiry*: students have the purest opportunities to act like scientists, deriving questions, designing and carrying out investigations, and communicating their results. This level requires the most scientific reasoning and greatest cognitive demand from students.

Within the inquiry-based framework of science education, a model of sequencing learning experiences is represented by the 5E model (Bybee, 1993) that leads students through five phases of learning: Engage, Explore, Explain, Elaborate, and Evaluate.
By synthesizing, the different phases can be described as follows:

(1) Engagement involves the setting of the learning environment in a way that stimulates interest and generates curiosity in the topic under study. The student mentally focuses on an object, problem, situation, or event. The activities of this phase should make connections to past and future activities. The connections depend on the learning task

and may be conceptual, procedural, or behavioural. Asking a question, defining a problem, showing a discrepant event, and acting out a problematic situation are always to engage the students and focus them on the instructional activities. The role of the teacher is to present a situation and identify the instructional task. The teacher also sets the rules and procedures for the activity.

(2) Exploration is the beginning of student engagement in inquiry, by searching for information, raising questions, developing hypotheses to test. This phase should be concrete and meaningful for the students. The aim of exploration activities is to establish experiences that teachers and students can use later to formally introduce and discuss content area specific concepts, processes, or skills. During the activity, the students have time in which they can explore objects, events, or situations. As a result of their mental and physical involvement in the activity, the students establish relationships, observe patterns, identify variables, and question events. The teacher's role in the exploration phase is first and foremost to select activities that lead to substantive concept building. The teacher’s role, then, is that of facilitator or coach. The teacher initiates the activity and allows the students time and opportunity to investigate objects, materials, and situations based on each student's own ideas and phenomena. If called upon, the teacher may coach or guide students as they begin constructing new explanations.

(3) Explanation involves the process of data acquisition and evidence-processing techniques for the individual groups or entire class (depending on the nature of investigation) from the information collected during the exploration. The process of explanation provides the students and teacher with a common use of terms relative to the learning experience. In this phase, the teacher directs student attention to specific aspects of the engagement and exploration experiences. First, the teacher asks the students to give their explanations. Second, the teacher introduces explanations in a direct and formal manner. Explanations are ways of ordering and giving a common language for the exploratory experiences. The teacher should base the initial part of this phase on the students' explanations and clearly connect the explanations to experiences in the engagement and exploration phases of the instructional model. The key to this phase is to present concepts, processes, or skills briefly, simply, clearly, and directly, and then continue on to the next phase.

(4) Elaboration is the state in which acquired information are discussed with peers and the teacher by acquiring extension of concepts to new situations and possible generalizations. Once the students have an explanation of their learning tasks, it is important to involve them in further experiences that apply, extend, or elaborate the concepts, processes, or skills. Some students may still have misconceptions, or they may only understand a concept in terms of the exploratory experience. Elaboration

activities provide further time and experience that contribute to learning. The teacher should provide opportunities for students to practice their learning in new contexts.

(5) Evaluation involves students' capacity to make judgments, analyses, and evaluations of their work, also in comparison with the work of their colleagues. As a practical educational matter, teachers must assess educational outcomes. This is the phase in which teachers administer formative or summative evaluations to determine each student's level of understanding. This also is the important opportunity for students to use the skills they have acquired and evaluate their understanding. This is also the time when the teacher determines whether students have met the performance indicators.

The experimental studies reported in this thesis are based on the development of guided and open inquiry-based learning paths whose procedural steps were designed by following the 5E model.

2.4 Facilitating Practices of Scientific Inquiry in Education

The relationship between the history of science and the development of scientific thinking in students as well as between scientific thinking and children's thinking has been a very important foundation of cognitive research on educational practices. Several philosophers of science (Nersessian, 1989; 1992; Thagard, 1992) as well as cognitive researchers (e.g., Burbules & Linn, 1991; Cobb, Wood, & Yackel, 1991; Scardamalia & Bereiter, 1994) have argued that there is a close relationship between the process of scientific thinking, learning science and science education. It seems that without considering the epistemological features of scientific inquiry, it is possible neither to understand the complex processes of learning scientific knowledge and developing scientific thinking nor to make successful "design experiments" (Brown, 1992) for facilitating higher-level practices of inquiry in education.

The seminal idea that practices of science learning at school should more closely correspond with processes of inquiry characteristic of scientific research has been argued for by several cognitive researchers (e.g., Bruner, 1960). The most common approaches to facilitate scientific thinking in education are focused on examining how individual students' abilities enabled them to engage in the processes of scientific inquiry (Scardamalia & Bereiter, 1994). In the traditional view, scientific thinking has been seen as a logical process which is free from the limitations of everyday thought. However, there is a considerable amount of evidence which shows that students do not think in accordance with scientific principles in everyday life but show many kinds of biases and misconceptions that rely more on realistic than abstract, formal procedures (see Miller et al., 2011).

On the other hand, an effective science instruction cannot be exerted only along theoretical perspectives but it necessarily has to be though within formal practices, involving scientific inquiry, in the context of everyday life. In this view, in order to help the students to apply proficiently what they learn at school to real-world situations, science learning should be situated in authentic context such as real-world problem solving (Savery & Duffy, 1996). In the following subsections, several learning and teaching strategies based on the resolution of problems and completion of research-like projects, are introduced and discussed.

2.4.1 Problem-based and Project-based Learning: Implications and criticisms

The need for developing effective strategies of teaching science and practical pedagogies promoting science learning by means of scientific research-like activities, has brought to the development of a Problem Based Learning (PBL) approach to science education. The term PBL refers to a fairly large area of student-centred teaching strategies, based on solution of real problems. A PBL model captures many of the key principles of a constructivist perspective of learning (Savery & Duffy, 1996), which suggests that for effective acquisition of knowledge, learners need to be stimulated to restructure information they already know within a realistic context, to gain new knowledge, and then to elaborate the new information they have learned. PBL can be defined as "experiential learning (minds-on, hands-on) organized around the investigation of real-world problems" (Torp & Sage, 2002, p. 15). Its characteristic features are the engagement of students as stakeholders in the problem situation, organization of the curriculum around a holistic problem, and creation of a learning environment in which teachers coach student thinking and guide inquiry (Torp & Sage, 2002).

This teaching approach was firstly experimented at the end of 60s at McMaster University (Canada), where the simulation and reconstruction of solutions of real clinical cases were included in medicine courses as curricular instruction (Barrows and Tamblyn, 1980). In the context of medical education, PBL was originally structured around five main objectives: construction of clinically useful knowledge, development of reasoning strategies, acquisition of effective self-directed learning strategies, increased motivation for learning, and becoming effective collaborators. These objectives were grounded on the notion that learning is not an accumulation of information, but a transformation of the individual who is moving toward full membership in the professional community. In PBL, in fact, group meeting should simulate the social process of knowledge construction. At the same time, in the United States, other PBL experiences involved schools of law, economics and architecture (Williams, 1992), where the analysis of systematic case studies were introduced as fundamental teaching practices.

Although there are variations and although it has been applied in other disciplines, practitioners of PBL acknowledge its medical school origins and tend to adhere to the structure and procedures systematized by Barrows. Here, some shareable characteristics of PBL as practiced in medical schools are reported:

1. Problems play a central role in the educational process.
2. Dialogue is the principal vehicle for problem solving.
3. An important part of work on a problem is identifying what needs to be found out in order to advance.
4. Small groups work collaboratively on solving the problem.
5. Information search and other tasks are distributed among group members instead of everyone's doing the same things.
6. The focus is on achieving a cognitive outcome rather than on producing an artefact or a presentation, thus distinguishing it from much of what is called 'project-based learning' (discussed below in this subsection).

A growing attention on PBL has been reported since the 90's, due to the convergence of various constructivist orientations toward pedagogical practices centred on a problematic vision of knowledge. The implementation of teaching strategies based on problem solving are primarily based on the activation of prior knowledge needed to start the preliminary analysis of the problem, the search for new information from activated prior knowledge, the restructuring of knowledge shared among colleagues and the development of semantic networks with new meanings (Schmidt, 1993). Learning should be also highly contextualized and the process of learning should be based on personal curiosity and the social construction of knowledge, both promoting the discovery and treatment of new problems. In a further synthesis by Savery and Duffy (1996), the fundamentals of PBL are substantially identified in the following design principles: (i) the learning objectives should be put in relation with real problems (or recognizable as real-life problems) and should generate other problems; (ii) teachers should play the role of facilitators at metacognitive level, providing the students with an initial amount of information about a problem, modelling students' hypothesis-driven thinking and encouraging learners to be reflective by means of metacognitive questions (for instance, by asking students to explain why they consider a solution to be good or why they need a particular piece of information).

Carl Bereiter and Marlene Scardamalia (2000) proposed to distinguish between "pbl" and "PBL", identifying the term written in lower case with an indefinite range of educational approaches that give problems a central place in learning activity, while the uppercase term is used to indicate more structured practices where, beyond the centrality of the problem, the procedures of analysis, discussion, sharing, and solution of the problem are particularly addressed. Within this more structured approach, a specific teaching/learning strategy based on problem-solving takes the name of project based learning (discussed below in this subsection).

The PBL approach to science education can be considered as the convergence of multiple pedagogical perspectives towards an educational philosophy that is strongly centred on problem solving. In this respect, Finkle and Torp (1995) define PBL as "a curriculum development and instructional system that simultaneously develops both problem solving strategies and disciplinary knowledge bases and skills by placing students in the active role of problem-solver confronted with an ill-structured problem that mirrors real-world problems". It differs from more ‘‘traditional’’ approaches to teaching in that the participants are encouraged to use self directed learning skills (placing emphasis on a person’s ability to seek out and assimilate relevant information to tackle a problem at hand) to analyse a given scenario, formulate key learning objectives within that scenario, and then collect whatever additional information they think will be needed to address their objectives. In PBL, class activities are constructed around a problem or problems. The instructor no long lectures. Instead, when the instructor integrates PBL into the course, students are empowered to take a responsible role in their learning. The instructor is not the authoritative source of information and knowledge. Students have to take the initiatives to inquire and learn; and the instructor must guide, probe and support students' initiatives. What students learn during their self-directed learning must be applied back to the problem with reanalysis and resolution. In Figure 2.2, a cyclic diagram describing the phases of a PBL environment is shown.

Read the problem (or scenario) carefully.

Identify the key issues.

Make sure you understand the main thrust of the problem (what you are being asked to do).

What do you already know that is relevant to this problem? (Prior knowledge).

What do you need to find out in order to solve this problem? (New knowledge).

How are you going to find out what you need to know?

What resources are you going to consult? Resources can take many forms, including books, articles, reports, web sites, people with particular expertise.

How are you going to assess the quality or reliability of those resources?

What do you think is the best solution to this problem? Why?

Remember that there is no "correct" solution to real life problems- all solutions will have their advantages and disadvantages.

Figure 2.2 The PBL Cycle.

The posing of a problem represents the starting point of the learning cycle. In this phase the students are guided by the teachers through the key issues characterizing *the problem* with the aim of stimulating the students to understand which steps they need to carry out in order to face the problem effectively. In the second stage, *the knowledge*, the students should be guided by the teachers to focus on what knowledge contents they already held in the specific context of the problem under investigation and what they need to know to further explore the route towards problem solutions. Subsequently, the students are stimulated to explore the available *resources*, such as books, articles, reports, web sites, people with specific expertise, with the aim to find what they may need to know to solve the problem. In the last phase, the *solution*, a reasoning effort is required to the learners who are stimulated to think about effective solutions to the problems. In this phase, it is important to let the students to understand that no absolutely correct solution exists, but the learners are invited to propose multiple solutions and discuss advantages and disadvantages of each one. The cycle is finally closed by returning to discuss about the problem and the proposed solutions, starting to address new problems that could arise.

PBL is about students connecting disciplinary knowledge to real-world problems. In this framework, the motivation to solve a problem becomes the motivation to learn. Studies suggest that PBL develops more positive student attitudes, fosters a deeper approach to learning and helps students retain knowledge longer than traditional instruction. Further, just as cooperative learning provides a natural environment to promote interpersonal skills, PBL provides a natural environment for developing problem-solving and life-long learning skills (Prince, 2004).

Similarly to PBL, Project-based science instruction (Krajcik et al., 1999) is an approach to science teaching/learning in schools that incorporates the key principles of a constructivist view of learning and, even equally oriented to problem solving, it is more specifically structured within a project.

Project-based science is characterized by:

1. a driving question that is meaningful to the learners and anchored in a real-world context;
2. student-conducted investigations that result in the development of products;
3. collaboration among students, teachers, and the community;
4. the use of technology, particularly computers, to help students represent and share ideas (Krajcik et al., 1999; Hoffman et al., 2003).

While conceptions vary, project-based learning has much in common with PBL and other experiential forms of learning. In project-based science, a driving question functions in the same manner as an ill structured problem in PBL. The driving question provides a clear but broad framework that affords ample opportunity for student-led investigations in real-world contexts. Students must generate their own questions within the framework afforded by the driving question, plan investigations, and evaluate their feasibility. The engagement of students in inquiry and the presence of a learning environment in which teachers act as facilitators and guide student questioning activity are both common characteristics of a family of instructional approaches related to PBL.

In a typical project, a group of middle-school science students might tackle a driving question, such as “What is in our water and how did it get there?”. The driving question, which is designed to be meaningful to the learners, provides a clear but broad framework that affords ample opportunity for student-led investigations in real-world contexts. Students must generate their own questions within the framework afforded by the driving question, plan investigations, and evaluate their feasibility. Once particular investigations are determined, students do background research as well as collect and analyze data, such as the results of tests of water samples collected from a local reservoir or class members’ taps. In this process, they work together, collaborate with their teachers, and often communicate with knowledgeable members of the community who can assist with various aspects of the investigation. Science content is addressed as it arises naturally out of the context of the investigations. The results of the process are artefacts (e.g., water samples, test results, graphs, charts) and products (e.g., reports, multimedia presentations, portfolios) produced by the students. Computer technology can play an important role throughout the process as a tool for gathering information, analyzing and representing data, and communicating the results. The project provides a pivot around which science learning, as well as learning in other subjects, can revolve.

Both PBL and project-based science emphasize collaborative construction of knowledge, problem solving, and transformation of traditional student and teacher roles (Hmelo-Silver, 2004). Collaborative learning refer to any instructional method in which students work together in small groups toward a common goal. It can be viewed as encompassing all group-based instructional methods, including cooperative learning, which instead can be defined as a structured form of group work where students pursue common goals while being assessed individually. Engaging students in inquiry and having students collaborate while learning may be helpful to promote active development of understanding by individuals, communication skills and shared meaning. This approach has been shown to be effective in promoting students’ science learning (Schneider, Krajcik, Marx, & Soloway, 2001).

Problem-based and Project-based learning differ in relatively minor ways. For example, while direct instruction is not used in a pure PBL approach, in project-based science teachers may sometimes provide direct instruction to students when they need information for problem-solving activities (Hmelo-Silver, 2004). With respect to PBL approaches experienced and described from Barrows onwards, project-based learning method is characterized by a greater attention to the design process and the research (usually collaborative) of effective and operational solutions to the posed problem, possibly focusing to concrete applications or trying to build "products" that give a sense of the analysis carried out, systematically using new technologies.

While the PBL, in the broadest sense, is spreading especially in adult education (at university the students usually show a greater autonomy and critical thinking skills), the Project-based Learning is gradually becoming the "form" through which the problem-based approach is practiced in schools.

Most of the literature tends to emphasize the positive implications of both Problem-based and Project-based approaches on at least the following two key concepts:

- Learning is enhanced when it is based on the activation of prior knowledge;
- Learning processes oriented to problem solving enhance the ability to develop, organize, remember and retrieve new knowledge.

These findings are supported by "empirical evidences" (Newman, 2004), which, on the contrary, are still insufficient to confirm the advantages of this approach for what concerns the ability of self-regulation of groups involved in finding a solution to a problem and about the motivating effect of collaborative effort that characterizes these methodologies (Hmelo-Silver, 2004). Against the expected superiority of PBL approach compared with traditional teaching methods, Woodward (1997), by analyzing the careers of groups of former students of Medicine, argued that there is no evidence that students coming out from universities where the curriculum is based on the PBL approach reach or are able to maintain a level of professional performance higher than students from a faculty teaching with lecture-based methods. Other findings confirmed the results of investigations carried out by Woodward (Kaufmann & Mann, 1999). On the other hand, a research study highlighted how doctors instructed by means of problem solving approaches had developed specific knowledge and high level skills with respect to colleagues with a traditional curriculum, in particular for what concerns the diagnostic capability in clinical cases and patient management, (Newman, 2004).

Experimental research has investigated in detail the differences in learning outcomes from students engaged in traditional activities compared to others involved in PBL activities. Contrary to expectations, no significant differences were found, even in different disciplines and in particular in those where the PBL approach has been most systematically practiced and documented: the teaching of medicine (Culver, 2000), studies of economics (Mergendoller et al., 2002) and studies in the legal field (Lee and Tsai , 2004). Even one of the few Italian studies on the subject (Piccinini and Scollo, 2006) comes to similar conclusions with regard to groups of students of computer engineering. They highlighted, in particular, the management difficulties of project-based laboratories without a critical rethinking of the role of teachers, whose action is crucial to support students activities within PBL. Other findings (Mergendoller et al., 2002) demonstrate the existence of differences in learning outcomes from students with reduced verbal communication skills, who get significantly better results in PBL environments compared to students with equal skills involved in traditional learning paths. This result supports PBL as a successful approach in contexts where it is necessary to customize the path to retrieve students in difficulty and/or enhance the different cognitive styles (Hmelo-Silver, 2004). Another evidence concerns the differences in performance found in PBL classes and traditional classes with the same initial interest in the subject in terms of motivation: in this case the results obtained by students engaged in problem-solving activities are significantly better, although this may mean either that the approach PBL is applicable with the most probability of success just in the presence of a strong motivation of learning.

All the research cited so far are always conducted on samples of college students. Thomas (2000) reviews several scientific contributions based on project analysis and comparative evaluations of the performance obtained by traditional and PBL groups of students: the conclusion is that, compared to what found at university, in the middle and high school significant differences in the results obtained from the PBL classes can be identified with respect to the traditional ones. However, these differences are not about the basic knowledge and skills acquired by the children, but a general successful result, in terms of measurable reduction of abandonment, greater participation, reduction of problems associated with student behavior (Demee-Benoit, 2006).

In summary, it seems that the PBL approach does not bring about a significant improvement of student performance, but can be very useful on motivational level and can help to address the problem of school abandonment, indirectly increasing the overall efficiency of a class. Several other studies and reports (referred to various types of schools and age groups, up to vocational training) reach the same conclusions (Bradford, 2005; Papastergiou, 2005). Thomas (2000) cites several studies about the capacity of the PBL approach to enhance problem-solving skills of students. At secondary school, students who are in PBL classes seem able to frame problems better than traditional students, but not necessarily to solve them. However, it is interesting to note that several studies cited by Thomas highlight how the PBL approach increases the critical abilities of students (critical thinking). Although Grant & Branch (2005) finds no specific improvements in decision-making skills, he finds that generally PBL students achieve higher critical attitudes of structuring knowledge domains and a greater susceptibility to metacognitive reflection. In essence, the PBL approach does not necessarily teach students how to solve problems better, but it can be a useful strategy to learn how to identify them with more clarity and to deal with them more critically. Moreover, if, on the one hand, students with lower school outcomes improve their performance, on the other they show greater difficulty in relating to the process and the tasks that it implies, while those with the higher skills tend to increase their capacity of self-organization (Thomas and MacGregor, 2005). It seems that problem-based approach does not facilitate the ability of PBL students to interact with each other and organize themselves as a group: teachers thinking that students are able to self-regulate in view of the solution of the problem addressed can indeed lead to unsatisfactory results and dispersive attitudes.

2.4.2 Progressive Inquiry Learning: Learning science as scientist discovery

The analogy between school learning and scientific inquiry is based on a close connection between processes of learning and discovery. Inquiry processes performed by scientists to produce new knowledge and inquiry carried out by students working for understanding new knowledge are based on the same kinds of cognitive processes. Learning, analogously with scientific discovery and theory formation, is a mental process oriented toward a more thorough and complete understanding. Although students' learning is focused on already existing knowledge, they may be engaged in the same kind of extended processes of question-driven inquiry as scientists. Within this framework, Scardamalia and Bereiter (1994) firstly hypothesized that scientific thinking could be facilitated in school by organizing classroom to function like a scientific research community and guiding students to participate in practices of progressive scientific discourse. Thus, schools should be restructured as knowledge-building communities through facilitating the same types of social processes, such as public construction of knowledge, that characterize progressive research teams and laboratories.

In this framework, progressive inquiry represents a pedagogical model which aims at facilitating the same kind of productive knowledge practices of working with knowledge in education that characterize scientific research communities (Hakkarainen, 1998) and a pedagogical and epistemological framework to support teachers and students in organizing their activities for facilitating expert-like working with knowledge (Muukkonen et al., 2004). It emphasizes shared expertise and collaborative work for knowledge building and inquiry by setting up the context, using questions, explanations, theories, and scientific information in the cycle of deepening inquiry. It is often used with computer-supported collaborative learning.

The progressive inquiry model describes the elements of expert-like knowledge practices in a form of a cyclic inquiry process (Figure 2.3)

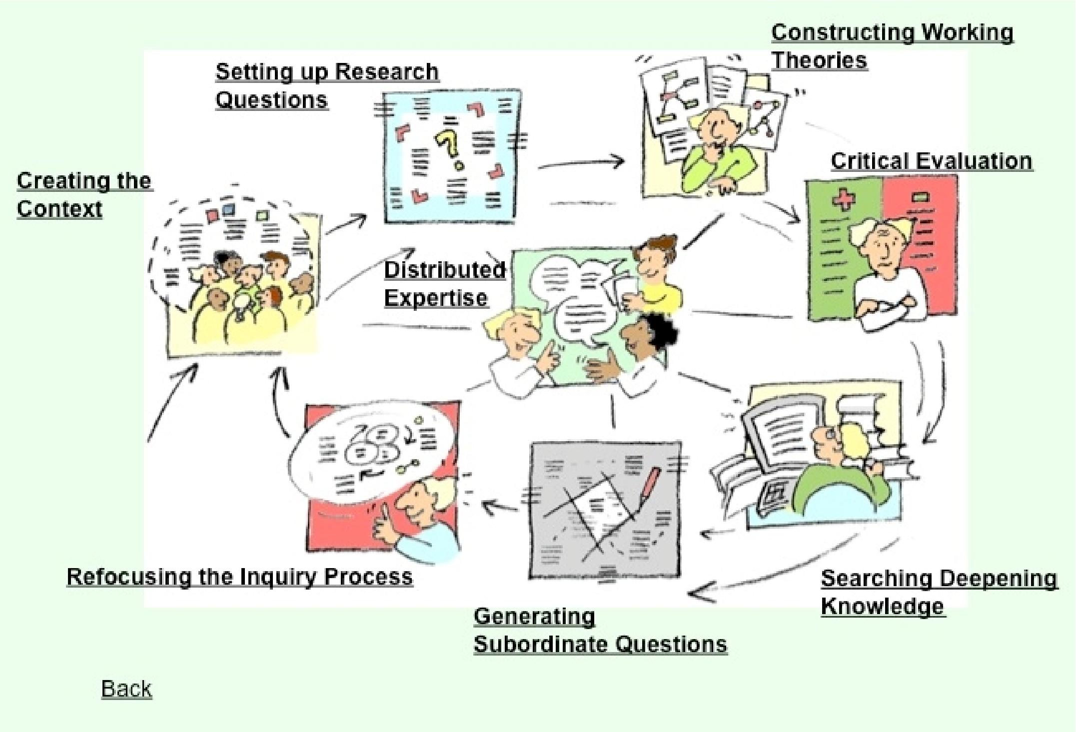


Figure 2.3 The Learning Cycle of Progressive Inquiry (Hakkarainen, 1998).

In a progressive inquiry process, the teacher creates a context for inquiry by presenting a multidisciplinary approach to a theoretical or real-life phenomenon, after which the students start defining their own questions and intuitive working theories about it. Students' questions and explanations are shared and evaluated together.

Educational practices should pay special attention to advancing skills for knowledge creation and collaboration, which should be supported by problem-based activities that simulate the practices of professional or scientific communities. In this kind of learning, students are seen as active and autonomous contributors who share valuable knowledge with each other, solve challenging open-ended problems, and systematically create new knowledge and explanations for the use of the community (Bereiter & Scardamalia, 2000). Limitations of human information processing can be overcome by relying on socio-culturally developed cognitive tools, artefacts, and good cognitive practices. All aspects of inquiry, such as generation of research questions, search for explanatory scientific information or construction of one's own theory, can be shared with other inquirers. Cognitive research indicates that advancement of inquiry can be substantially elicited by relying on socially distributed cognitive resources, emerging through social interaction between the learners, and collaborative efforts to advance shared understanding.

2.4.3 Model-based Inquiry: An epistemologically grounded alternative to the Scientific Method

The Oxford English Dictionary defines the Scientific Method (SM) as: "a method or procedure that has characterized natural science since the 17th century, consisting in systematic observation, measurement, and experiment, and the formulation, testing, and modification of hypotheses". The SM originated because of the need to define a process by which scientists, collectively and over time, may endeavour to construct an accurate (that is, reliable, consistent and non-arbitrary) representation of the world. Recognizing that personal and cultural beliefs influence both our perceptions and our interpretations of natural phenomena, scientists still today aim, through the use of standard procedures, to minimize those influences when developing a theory. In summary, the main aim of the application of the SM is that to attempt to minimize the influence of bias or prejudice in the experimenter when testing an hypothesis or a theory.

The SM remains a durable icon that actively shapes how teachers and learners think about scientific practice. The SM is characterized by four main steps:

1. Observation and description of a phenomenon or group of phenomena.
2. Formulation of an hypothesis to explain the phenomena. In physics, the hypothesis often takes the form of a causal mechanism or a mathematical relation.
3. Use of the hypothesis to predict the existence of other phenomena, or to predict quantitatively the results of new observations.
4. Performance of experimental tests of the predictions by several independent experimenters and properly performed experiments.

If the experiment results confirm the hypothesis, this may be regarded as a new theory describing a law of nature. If the experiments do not bear out the hypothesis, it must be rejected or modified. The key feature in the description of the SM is the predictive power of the hypothesis or theory, as tested by experiment. It is often said in science that theories can never be proved, only disproved. There is always the possibility that a new observation or a new experiment will conflict with a long-standing theory, producing new knowledge.

However, the SM has many critical points and intrinsic problematic aspects that have been recently subjected to criticisms. As commonly implemented in secondary school classrooms up to undergraduate laboratories, the SM "emphasizes the testing of predictions rather than ideas, focuses learners on material activity at the expense of deep subject matter understanding, and lacks epistemic framing relevant to the discipline" (M. Windschitl, J. Thompson, M. Braaten, 2008). Common characteristics of worldwide science classrooms is that students often carry out a laboratory activity without deeply understanding what they are really doing, simply executing teachers' instructions, by following the SM steps, but missing a real comprehension of their actions (Banilower, et al., 2006; Roth & Garnier, 2007). In this perspective, the SM becomes a procedure, but not a way of thinking. The application of the SM as a mere execution of pre-ordered steps also reinforces the unproblematic image of science and oversimplifies the forms of reasoning beneath the complete understanding of a concept. Moreover, student questions are often based on what is interesting and rarely grounded in any initial model of what might influence the investigated phenomenon. Questions are typically provided to students by the curriculum or teacher. Probably the most crucial aspect of the SM is that it does not provide inquirers to develop an initial platform of understanding to inform their questions. Students collect data that are used to characterize only how outcomes are related to conditions.

Windschitl and collaborators (2008) suggested to develop authentic practice of inquiry by following five epistemic features of scientific knowledge:

1. scientific knowledge, in the form of models or theories, is advanced by proposing new hypotheses that express possible relationships between events, processes, or properties within these models or theories (*testable*);
2. scientific ideas can change in response to new evidence or because a phenomenon is conceptualized in an entirely different way (*revisable*);
3. the goal of science is to provide causal accounts of events and processes, as opposed to accumulating descriptive detail about phenomena or merely seeking patterns (*explanatory*);
4. causal accounts often involve theoretical or unobservable processes that can only be inferred from empirical observation (data) and that scientific argument aims to persuade others that explanations based on these inferences account most adequately for the observations (*conjectural*);
5. scientific knowledge, in the forms of models and theories, are the prime catalysts for new predictions, insights about phenomena, and hypotheses for testing; they are not simply "end-products" of inquiry (*generative*).

Those researchers explicitly state that “authentic forms of inquiry for school science can be grounded in these five ideas and, particular, in reasoning with and about models. This is because epistemic issues such as testability, conjecture, explanation, principled revision, and generativity are embodied most clearly and commonly in scientists’ (and students’) work with models as representations of ideas about the natural world.”

In table 2.1 we briefly summarize the key features of scientific knowledge suggested by Windschitl and co-workers (2008), discussed in the context of inquiry as commonly practiced within the SM or by following a Model-based Inquiry (MBI) approach.

Table 2.1 Epistemic features of Scientific Knowledge

Epistemic Features Scientific Knowledge is:	Inquiry based on the **Scientific Method**	**Model-based Inquiry**
1. Testable and revisable	Hypotheses (predictions) are tested, but not revisable (they are not theories).	Ideas (models) are tested and revised.
2. Explanatory	Conclusions summarize trends and patterns in the data, but often do not include explanations.	Patterns in data are structured within models to explain the observed phenomenon.
3. Conjectural	Seldom classroom inquiries go beyond the data.	Explanations account for observations with underlying causal processes.
4. Generative	Theories considered to be an end-product, but often not further discussed.	Models/theories used to generate new conceptions or new predictions.

The basic difference between the two inquiry-based strategies relies on their general objective: The application of the SM is often aimed at finding patterns in the data collected about the observed phenomenon in order to test a hypothesis, while the MBI is more oriented toward the development of “defensible explanations of the way the natural world works”. In using “explanations,” the authors of this approach emphasize that the end product should be a statement that helps us understand some aspect of the world at the level of causation. This explanation is embodied in the testable, modifiable representations of scientific ideas, i.e., models. “Defensible” alludes to the use of evidence in creating such an explanation. The “natural world” focuses learners on processes, events, or structures in the general domains of science (biology, physics, earth science, or chemistry).

Inquiry as commonly practiced in classrooms following the steps of the SM usually shows little possibility for the students to connect empirical data and unobservable processes, without any significant mental effort for finding explanations. In this context, the students limit their activity to follow a pre-ordered list of actions aimed to test a hypothesis or, more often, to confirm a natural law already studied. Moreover, the experiments carried out in laboratory by the students acting in such a mechanical way could bring about to fruitless activities, even loosing contact with the content of the subject.

On the other hand, the MBI approach is more grounded in content and facilitate the students to connect empirical data with underlying causes, by testing an idea and going beyond how something happens to why something happens. The teachers should promote investigations emerging from a motivating interest in some aspect of the natural world, providing the students with resources or experiences stimulating the development of a tentative representation (i.e., model) of the phenomenon. This model should suggest processes, properties, or structures (these may or may not be directly observable) which are potentially explanatory of the target phenomenon. Windschitl and collaborators (2008) assert that "developing such representations is important to the entire class because (1) the representations can be shared with others and critiqued, (2) they can help learners see connections between ideas in ways that other representations (such as oral explanations) will not allow, (3) they can be changed as the class (or individual) learns more, and (4) perhaps most importantly, the explicit production of models helps teachers recognize gaps".

In summary, the SM, as it is commonly practiced in school today, oversimplifies scientific activity and distorts its epistemology and its goals. It also fails to engage learners in deep understanding of content. The MBI offers a more epistemologically congruent representation of how contemporary science is done and, from the disciplinary point of view, the activities that characterize MBI embody the main epistemic features of scientific knowledge. Scientists engage in a wide range of activities. They watch other members of their profession perform demonstrations of new equipment and techniques, they build laboratory skills over time, they replicate other scientists' experiments, they invent new technologies, they conduct thought experiments, they conduct library research, and they use knowledge to solve practical problems. All of these activities are valuable for school science learning as well, but there are particular practices that are integral to the core work of science, which is mostly organized around the development of defensible explanations of the way the natural world works. For scientists, these explanations come from the process of developing models and hypotheses and then testing them against evidence derived from observation and experiment. In this way new knowledge is produced. Learners should be guided by the teachers to develop the necessary reasoning skills to perform the same model-based thinking tasks the scientists do in their everyday research activities.

2.5 The question of the effectiveness of Inquiry-Based teaching

An important aspect of inquiry-based science education is the use of *open learning*. Originally developed by a number of science educators, including John Dewey and Martin Wagenschein and founded as a teaching method on the work of Célestin Freinet in France and Maria Montessori in Italy, open learning is supposed to allow pupils a self-determined, independent and interest-guided learning. In this context, the term *active learning* has been used to refer to several models of instruction that focus and entrust the responsibility of learning on learners. Bonwell and Eison (1991) discussed a variety of methodologies for promoting an active learning approach to instruction in their report to the Association for the Study of Higher Education (ASHE). They cite literature which indicates that learners must read, write, discuss, and be engaged in higher-order thinking tasks as analysis, synthesis, evaluation and solving problems. They suggest learners work in pairs, discuss materials while role-playing, debate, engage in case study, take part in cooperative learning, or produce short written exercises, etc. In summary, active learning engages students in two aspects: “doing things and thinking about the things they are doing” (Bonwell and Eison, 1991)

In open teaching, the students are either left to discover by themselves what the result of the experiment is, or the teacher guides them to the desired learning goal but without making it explicit what this is. In this view, a *discovery learning* can occur whenever the student is not provided with an exact answer but rather the materials in order to find the answer by themselves. Jerome Bruner is often credited with originating discovery learning in the 1960s, but his ideas are very similar to those of earlier writers (e.g. John Dewey). Bruner argues that "Practice in discovering for oneself teaches one to acquire information in a way that makes that information more readily viable in problem solving" (Bruner, 1961, p. 26). Discovery learning takes place in problem solving situations where the learner draws on his own experience and prior knowledge and is a method of instruction through which students interact with their environment by exploring and manipulating objects, wrestling with questions and controversies, or performing experiments. In support of the fundamental concept of discovery learning, Bruner (1961) suggested that students are more likely to remember concepts if they discover them on their own as opposed to those that are taught directly. While his article is cited as the fundamental framework for discovery learning, Bruner also cautioned that such discovery could not be made prior to or without at least some base of knowledge in the topic (Alfieri et al., 2011).

Although these form of instruction, supported by the work of learning theorists and psychologists Jean Piaget, Jerome Bruner, and Seymour Papert, has great popularity, there is some debate in the literature concerning its efficacy (Mayer, 2004). Because students are left to self-discovery of topics, researchers worry that learning taking place may have errors, misconceptions or be confusing or frustrating to the learner (Alfieri et al., 2011).

The science education community has published a wide range of findings about inquiry-based teaching and learning including inconclusive, mixed, or negative results that question its effectiveness (Colburn, 2008). In the review article entitled “Why Minimal Guidance During Instruction Does Not Work: An Analysis of the Failure of Constructivist, Discovery, Problem-Based, Experiential, and Inquiry-Based Teaching”, Kirschner, Sweller, and Clark (2006) provide evidence against the effectiveness of inquiry-based materials and related teaching strategies. The studies they reviewed include some that showed how pure discovery teaching methods can lead to frustration (Brown & Campione, 1994), some that showed how discovery learning is inefficient because it can lead to false starts (Carlson et al., 1992), and some that found support for direct instruction over discovery learning (Moreno, 2004).

Kirschner et al. (2006) equate inquiry with other instructional approaches as being characterized by “minimal guidance during instruction”. In this respect, Hmelo-Silver et al. (2007) describe research on the many forms of scaffolding involved in inquiry-based teaching and firmly disassociate it from the discovery learning examined in the studies cited by Kirschner et al. (2006). Inquiry is not only far from being “minimally guided”, but in fact relies on significant scaffolding to guide student learning.

Consistent with their lack of distinction between different instructional models, Kirschner and co-workers (2006) highlight the work of Klahr and Nigam (2004) as providing particularly significant evidence against inquiry-based materials and teaching, because the authors “not only tested whether science learners learned more via a discovery versus direct instruction route but also, once learning had occurred, whether the quality of learning differed”. The work by Klahr and Nigam (2004) has indeed stimulated review and discussion of the relative importance of direct instruction and discovery learning as instructional approaches for science teaching, but in neither article do the authors make any claims about inquiry. Furthermore, the authors’ operational definition of direct instruction in these studies has been shown by Bybee et al. (2006) to incorporate many aspects of an inquiry-based instructional model, and their operational definition of discovery learning has been shown by Blanchard et al. (2008) to involve no teacher scaffolding. Finally, in a study examining acquisition of the same learning goal as Klahr and Nigam (2004) by different instructional approaches, Dean and Kuhn (2006) found that direct instruction was “neither a necessary nor sufficient condition for robust acquisition or for maintenance over time”.

In their response to Kirschner et al. (2006), Hmelo-Silver et al. (2007) discuss the results of a study by Hickey et al. (1999) that found that students using the inquiry-based GenScope learning environment showed significantly higher learning gains than students in comparison classrooms that did not incorporate inquiry-based strategies and materials. Using performance on state standardized tests as the measure of student learning, Geier et al. (2008) found significantly higher scores among middle school students using inquiry-based materials compared to students using traditional materials. The effects were both cumulative (more exposure to inquiry-based units resulted in higher achievement on the tests) and enduring (the learning gains were evident a year and half after participation in the units). Hmelo-Silver et al. (2007) also describe a study by Lynch and co-workers (2005) in which students receiving inquiry-based instruction outperformed students in comparison groups, regardless of ethnicity, socioeconomic status, gender. Hmelo-Silver et al. (2007) conclude: ‘‘there is growing evidence from large-scale experimental and quasi-experimental studies demonstrating that inquiry-based instruction results in significant learning gains in comparison to traditional instruction.’’

Similarly to the Hmelo-Silver et al. (2007) conclusion, Colburn (2008), in a review of studies examining the effectiveness of inquiry-based teaching up to the mid 1990s, notes: “Most studies I examined supported the collective conclusion that inquiry-based instruction was equal or superior to other instructional models for students producing higher scores on content achievement tests”.

Finally, recent studies by Blanchard et al. (2008), Nottis et al. (2010), Lindsey et al. (2012) shine further light on questions regarding the effectiveness of inquiry-based curriculum materials and teaching strategies. Blanchard et al. (2008) compared learning gains in middle and high school students after being taught a forensic unit by either inquiry-based or traditional approaches. Their study, involving 1,800 students and 24 teachers from seven schools, showed significantly higher post-test scores among the students taught by a guided inquiry approach, as compared to students taught by traditional methods. The pedagogical effectiveness of incorporating guided inquiry-based activities, concerning the topic of heat transfer, has been observed in courses for chemical engineering undergraduates, who achieved higher overall scores on answering a post-instruction concept inventory (Nottis et al., 2010). The recent study by Lindsey et al. (2012) has shown positive shifts in the conceptual understanding and problem-solving categories of the Colorado Learning Attitudes about Science Survey (CLASS) by pre-service and in-service teachers experiencing the *Physics by Inquiry* curriculum.

Chapter 3

The ESTABLISH Project and the experimentation at secondary school

3.1 The ESTABLISH project

Inquiry based teaching methodologies have been suggested as a way to encourage and engage students in the study of science and mathematics by increasing their interest and also by stimulating both students and teacher motivation. However, the widespread implementation of such a methodology will only occur with inclusion and participation of all partners in education, both formal and informal.

ESTABLISH (European Science and Technology in Action: Building Links with Industry, Schools and Home) is a four year (2010-2013) multidisciplinary project funded by the European Commission's Framework 7 Programme for Science in Society, aimed at promoting and developing Inquiry-Based Science Education (IBSE) in European secondary schools. The ESTABLISH group consists of over 60 partners from 11 European countries, working with the aim of providing appropriate teacher education and to adopt and trial actions to bridge the gap between the science education research community, science teachers, students, parents, local industry as well as policy makers in order to facilitate the uptake of inquiry-based science teaching. The project has informed the development of teaching and learning materials to support both in-service and pre-service teachers with appropriate educational scaffoldings for a professional development, suitable designed to promote the use of IBSE in secondary school classrooms across Europe. The rationale for this project lies in creating authentic learning environments for science by bringing together and involving all stakeholders that make change possible. Teachers themselves are active partners in this project both as developers, researchers and agents for change. At this regard, the outcomes of this project would be also the development of suitable models of teacher education for inquiry based teaching and the identification of best practice in guiding change through all the stakeholders involved in science and science education.

3.1.1 The ESTABLISH model: stakeholders' involvement in science education

This project brings together the key communities that are stakeholders in second level science education to work together to generate and implement innovation in the classroom for the teaching and learning of science and technology. The stakeholders are:

1. Teachers and teacher educators of science, including science teacher networks;
2. The scientific community, both local enterprises and multinational industry as well as the science research community;
3. The students of science in second level schooling;

4. The parents of the students mentioned in 3;
5. The policy makers in science at second level, including curriculum developers and assessment agencies;
6. National science education researchers

The relationship between the stakeholders is quite complex, given the unequal strength of each relationship. For example, parents have a strong influence on the students, but in a different way with respect to that of the teachers; the business community is interested in the advantages they will acquire through the skills of the people they will employ, while policymakers attempt to find consensus between parents, teachers and business in their respective country. Thus, there are many societal demands placed on science education. Parents want their children to 'do well', 'go to college' or 'get a job'. Teachers want their students to do well as a social conscience aim but also out of professional pride, while business needs employees with an ability to innovate, and policymakers want the economy to grow. However, as shown above, many other communities need to actively share and understand the common goals and methodologies used to attain them. The interactions proposed by ESTABLISH are shown in Figure 3.1 and can be contrasted clearly with the traditional modes of interaction.

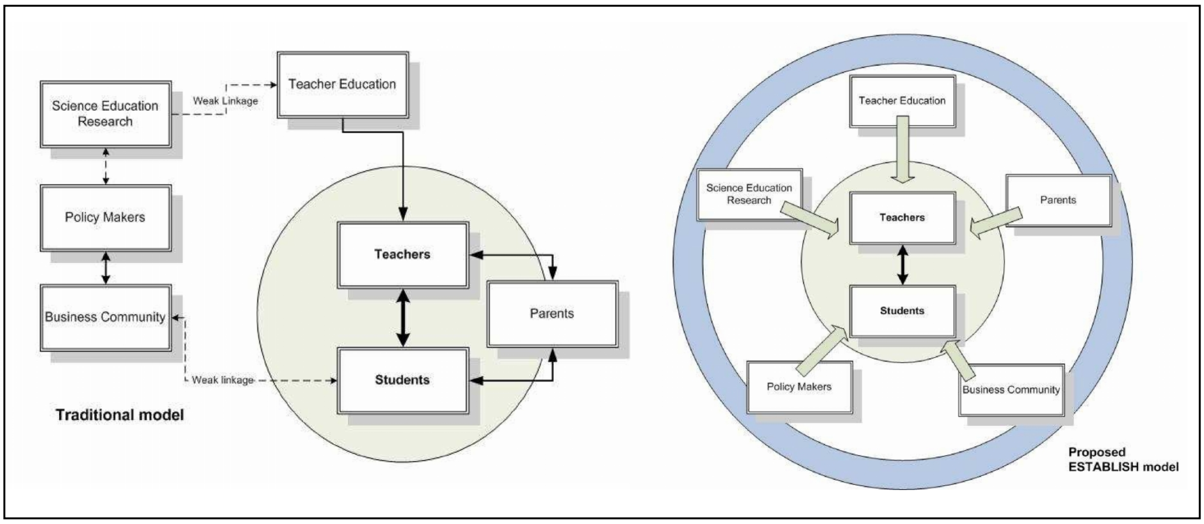


Figure 3.1 Traditional model of interactions among education stakeholders and the proposed ESTABLISH model.

In maximising potential in the students, all of the stakeholders have to share a common vision for the output. It is widely accepted in science education research, that much of the science education research output is rarely implemented in schools or even impacts on the methodology, curriculum or assessment. This clearly indicates a mismatch between the knowledge gained by the researchers in science teaching and learning and the implementation of it by teachers, curriculum developers and assessment bodies. In the past, the stakeholders have pursued their individual goals in isolation. The ESTABLISH project has worked to draw together the communities in order to develop a common vision of successful science education through an effective pedagogy. Maximising the potential of learners can be best achieved through restructuring teacher education (both pre-service and in-service) to support teachers to adopt an inquiry-based approach in the classroom, by collaborative intervention between the relevant stakeholders as outlined above. The project main goal has been that to reconnect the stakeholders to establish a new way of thinking about how science is learned and to help all stakeholders to focus on and understand the educational benefits and implementation requirements of an inquiry based methodology.

3.1.2 Project Objectives

The overall objective of the project concerns the implement of inquiry-based approaches to science education for second level students (age 12-18 years) on a widespread scale across Europe. The work of the project partners, through the involvement of the stakeholders in science education within a collaborative environment and formal and informal educational actions, has been focused on the achievement of:

1. the increase of student's intrinsic motivation in science and technology;
2. the improvement of scientific literacy and promotion of student involvement in experiential learning;
3. greater implementation of IBSE methodologies by teachers;
4. more informed science career choices by students.

The specific project objectives (PO) of ESTABLISH are:

PO1. To facilitate and implement an inquiry-based approach in teaching and learning of science and technology across Europe, through the following actions:

(i) To trial and evaluate teaching and learning inquiry-based materials and localise where applicable, based on relevance to current industry and research in science, gender considerations, cultural and local pre-conditions.
(ii) To provide support for teachers to successfully implement this approach.
(iii) To further develop and implement the teaching and learning materials across Europe.
(iiii) To share and disseminate inquiry-based approaches and teaching and learning materials for science education.

PO2. To stimulate learning and promote intrinsic motivation in students and identify career opportunities in science and technology for both men and women, by providing with authentic experiences from across research and industry.

PO3. To foster a mutually beneficial relationship between industries/research, teaching communities and the local education system, for the ongoing advancement of science and technology.

PO4. Encourage sharing of experiences from across all the partners over Europe to deliver model(s) of best practice for incorporation of inquiry based teaching in classrooms and in teacher education.

PO5. Evaluation of model(s) of best-practice in driving curricula and pedagogical change and this includes the involvement of all stakeholders from parents to policy makers.
PO6. Widespread dissemination of resources and models of best practice to the wider EU community.

There is a widespread variation in the science curricula across Europe and additionally, the nature of the science taught varies with the age of the students and their gender. In some countries, students take an integrated science curriculum throughout their second level schooling (e.g. in Sweden) where as in Poland and Cyprus, students study separate science subjects from the age of 12 onwards. Inquiry based teaching methods have been suggested as a way to encourage and motivate students in science and mathematics by increasing student interest. International reports have identified the need for an "engaging curricula to tackle the issue of out-of date and irrelevant contexts and to enable teachers to develop their knowledge and pedagogical skills". Second level teachers are then targeted to implement the IBSE methodology.

While indeed, increased interest and motivation in science by students is the overall objective, this can only be achieved by involvement and training and support of the science teachers to use this methodology in their classrooms. Teachers (both experienced and teacher trainees) must experience the benefits themselves of IBSE. This project aims to enable teachers to adopt an inquiry-based approach in their classrooms for more effective science teaching. Therefore, a key part of this project has been to determine the attitudes of the teachers to IBSE throughout the implementation and any changes that occur. If teachers become more open in the process and are provided with authentic scientific experiences, then they will be more confident in their teaching.

The IBSE approach encourages active involvement by students in their learning and as such promotes a greater level of student engagement than traditional approaches. However, for any change in teaching methodology and /or curricula, evidence must be clearly shown of its value in teaching and its impact on student learning. Therefore the effect of this project on student learning has to be determined by focusing on the development of student's analytical skills and learning. The impact on intrinsic motivation for learning science, i.e. the impact on student's appreciation of the importance of science and technology in society and the impact on student's inclination towards taking up careers in science has to be evaluated as well.

An inquiry-based approach is thought to assist less able learners attain higher grades and motivate medium to upper ability learners to 'do' science. The implementation of IBSE in schools has to be achieved through the provision of the resources above to teachers and through innovative science teacher education, at both pre-service and in-service level, all of which have been developed by the collaborative efforts of experienced science education researchers and teacher trainers from across Europe. This will include the:

1. provision of training packages for inquiry based teaching,
2. workshops for all the stakeholders,
3. provision of inquiry based teaching materials.

Each member of the consortium has committed to educate a number of teachers using the above resources for IBSE. The number of teachers involved in each county averages about 5 teachers per country in the pilot phase with an average of 50 additional teachers (pre-service and in-service) per annum in each country in the dissemination phase. Each country has been involved in slightly different forms of teacher training – from seeking volunteer teachers to being part of the national in-service teacher education.

From analysis of the effectiveness of IBSE implementation in schools, the consortium should be able to develop models of best-practice for teacher education in IBSE for dissemination across Europe (PO4). A critical outcome of this project will identify the factors that are necessary in driving educational change at a national/European level (PO5). This will require input by all stakeholders.

The ESTABLISH project team is committed to sharing and disseminating best practice (PO6) in inquiry-based pedagogy for science education among teachers, science education researchers, teacher trainers, students, parents, policymakers/curricula developers and industry. This will include sharing teachers' experiences with existing and future science teachers through European teacher networks, conferences and publications. It will also disseminate the effectiveness of the cultural adaptation of resources and the role of industry in communicating and promoting science and technology. The project will also disseminate findings on the impact of ESTABLISH on young people's interest in science, including both girls and boys.

This project hosted a substantial mid-project conference for representative teachers of ESTABLISH from each country to come together to share their experiences of IBSE in their classrooms.

3.1.3 ESTABLISH general guidelines to unit development

In ESTABLISH, resources related to key science topics have been combined into workable teaching and learning units. The starting point for this were the resources provided by the consortium partners and also the existing resource called "Science and Technology in Action" (STA), (www.sta.ie) which has already been developed in collaboration with industry, national policy makers, in-service teachers, parents and national teacher support service in Ireland. STA has been chosen as a starting resource as it covers a wide breadth of topics and enforces the awareness of the critical importance of science and technology to our economy and society. The links with the stakeholders will be maintained in the adaptation of the materials for European use and for inquiry based teaching and learning.

Common scientific themes that are applicable across Europe have been identified in key areas such as energy, environment, genetics, pharmaceuticals and appropriate materials identified from STA and other resources contributed by the consortium partners. These materials have been adapted to strengthen the IBSE methodology and also to account for specific cultural differences. Stakeholder input, particularly from industry, and teachers have ensured the relevance and authenticity of the materials. In total, 12-16 teaching units have been selected with approximately 3 units addressing each of the subject areas Biology, Chemistry, Physics, Technology and Multidisciplinary science. The criteria for each teaching unit were that they conform to our definition of IBSE, encouraging and facilitating students to be active participants

Each teaching unit went through a pilot test then revision followed by implementation in teacher education. All of the ESTABLISH partners have brought their expertise and experiences of IBSE to the consortium and the sharing of ideas and experiences has informed the implementation of IBSE in schools, particularly in teacher education, both at pre and in-service. The collection of partner experiences and national experiences will result in generation of models of best practice in IBSE.

To facilitate IBSE based on the STA units, the units will be enriched by activities in which students are active with:

- computer-based measurements,
- video measurements,
- modelling activities, as well with analytical tools as well numerical tools,
- control activities.

3.2 The contribution of UoP-PERG (University of Palermo, Physics Education Research Group) to ESTABLISH: Development of the teaching-learning unit entitled “A low Energy House”

The Italian partners of ESTALISH have actively participated to the project by providing many different contributions. One of these concerned the preparation an articulated GI-based teaching-learning unit on thermal science. In fact, by following the project’s guidelines, the Physics Education Research Group of the University of Palermo has developed a teaching/learning unit about the actual problem of applying energy saving strategies on the construction of low energy houses. As a member of UoP-PERG, I was personally involved in the project and actively participated to the preparation and experimentation of this inquiry-based teaching-learning path.

The unit, available at http://www.uop-perg.unipa.it/establish/classroom_materials.htm, is aimed at engaging high school students in designing and building an energy-efficient scale model house through the understanding of the relevant concepts in the content area of energy flow in thermal systems. The learning project intends to introduce pupils to the basic knowledge of thermal science and infrared imaging thermography. The unit is developed into four subunits, each one focused on a specific problem to address and, in particular, on the analysis of the different effects produced by the three mechanisms of thermal energy transfer (conduction, convection and radiation).

In details:

- Subunit 1guides students in the construction of a model house and in making explicit the different factors that contribute in heat dispersion and energy consumption to maintain warm the house. The effects produced by each mechanism of energy transfer are deeply analysed in the other three subunits, which are developed around a particular problem that guides the inquiry.
- Subunit 2 analyses the role of different materials in heat dispersion by developing the relevant concepts connected with energy transfer through conduction.
- Subunit 3 analyses energy transfer in fluid material and the main concepts connected with the convection process.
- Subunit 4 introduces the concept of energy transfer by thermal radiation, analysing the different effects of solar radiation spectrum.

The global content area of the unit concerns the topics of energy and power in thermal systems. The subunits are mainly devoted to 14-16 year old students. However, a specific deepening, involving more mathematization of data analysis and theoretical formalization, is designed for 16-18 year old students. The estimated duration of the whole unit is 30 hours. However, it could be used partially and/or at different deepening levels. The unit uses hands-on activities, scientific simulations and probe-ware measurements as tools to promote an Inquiry based approach.

3.2.1 Content Knowledge of the unit

The main physics concepts addressed in the unit are: temperature, thermal energy and heat. The achievement of a meaningful understanding of such concepts involves many difficulties that are often connected with the different definitions provided in the textbooks with respect to the meanings they have in the everyday life. For this reason we, here, clarify the main definitions of the involved concepts.

The temperature of an object is defined as a measure of the average kinetic energy of the particles of an object. Thermal energy is the total sum of all the energies of the object particles. As a consequence, thermal energy and temperature are related though different: temperature is proportional to the average kinetic energy of the particles; thermal energy is the total amount of the kinetic energy of the object particles. In the unit we discuss about thermal energy arising from the fact that particles of matter are in constant motion and that this motion relates directly to the state of matter of the object (solids, liquids, or gases). How fast these particles move affects the object temperature. Faster particles mean higher temperature. Moving particles possess kinetic energy.

Transfer of thermal energy between systems can happen through three different processes:

- Conduction – direct contact between objects at different temperatures;
- Convection – through a fluid motion;
- Thermal radiation – by electromagnetic waves;

The term heat involves the quantity of energy transferred from one place in a body or thermodynamic system to another place, or beyond the boundary of one system to another one when in thermal contact, when the systems are at different temperatures. In this description, it can be considered an energy transfer to the body in any other way than the mechanical work performed on the body

Transfer by conduction is the transfer of thermal energy between regions of matter due to a temperature gradient. Heat spontaneously flows from a region of higher temperature to a region of lower temperature, temperature differences approaching thermal equilibrium. On a microscopic scale, conduction occurs as rapidly moving or vibrating atoms and molecules interact with neighbouring particles, transferring some of their kinetic energy. Heat is transferred by conduction when adjacent atoms vibrate against one another, or as electrons move from one atom to another. Conduction is the most significant mean of heat transfer within a solid or between solid objects in thermal contact. Conduction is greater in solids because the network of relatively fixed spatial bounds between atoms helps to transfer energy between them by vibrations.

The transfer of thermal energy by convection refers to the process of energy exchange through a substance by mean of fluid currents. Convection is usually the dominant form of heat transfer in liquids and gases. Although often considered a distinct mechanism of heat transfer, convective heat transfer involves the combined processes of conduction (heat diffusion) and advection (heat transfer by bulk fluid flow). The term convection can refer to transfer of heat with any fluid movement, but advection is the more precise term for the transfer due only to bulk fluid flow. Convection can be "forced" by movement of a fluid by means other than buoyancy forces (for example, a water pump in an automobile engine). In some cases, natural buoyancy forces alone are entirely responsible for fluid motion when the fluid is heated, and this process is called "natural convection."

All matter with a temperature greater than absolute zero emits thermal radiation. Inter-atomic collisions cause the kinetic energy of the atoms or molecules to change and this results in charge-acceleration and/or dipole oscillation which produces electromagnetic radiation. The wide spectrum of radiation reflects the wide spectrum of energies and accelerations that occur even at a single temperature, because of the thermal motion of charged particles in matter. Thermal radiation is the transfer of energy, called radiant energy, by electromagnetic waves, which may travel through the vacuum space or matter.

Transfer by conduction and convection involves a direct contact between two or more bodies at different temperatures. In this case we specifically say that heat is exchanged between the bodies. Transfer by thermal radiation involves the interaction between one body and the electromagnetic field produced by a distant body.

The general content objectives of this unit involve the ability to:

- differentiate between the concept of heat and the quantity of temperature;
- understand the concept of thermal equilibrium and thermal process;
- differentiate among the mechanisms of conduction, convection, and radiation.

Within the specific instruction addressed by the unit, the students are asked to:

- provide useful examples of how conduction, convection, and radiation are considered in choosing materials for buildings and designing an house model;
- explain how environmental factors such as wind, solar radiation, and external ambient temperature affect the design of an house and the choice of the materials.

3.2.2 Specific aspects of IBSE character in the unit

The unit has been designed as an instrument to be used to develop students' ability to plan investigations, develop hypothesis, distinguish alternatives, searching for information, constructing models and debating with peers. It covers different types of inquiry activities, from interactive demonstration to open inquiry. The main problem of projecting a low energy house is divided in four sub-problems which are addressed in the different subunits that are designed to develop an increasing student participation and independence. The unit can be implemented in different ways, and for each subunit emphasis can be given on different elements of inquiry. However, in each subunit a progression in assigning autonomy to student is foreseen by making the suggested questions more general.

In each subunit, the teacher may start with either a series of questions or with an interactive demonstration, like in subunit 2, where the initial demonstration poses the problem to investigate and the process of inquiry can be developed in different steps (some of them are suggested by the activities that lead to questions for further investigations). All the activities may be guided, bounded or lead into open inquiry settings. However, the initial activities given in each sub-unit will form the background for further open inquiry activities to be performed by students.

In order to focus on the different skills connected with the inquiry process, the starting point of each activity is a well defined problem whose solution requires students' engagement, raising questions and developing hypotheses. The teacher interactions with the students during their inquiry activities is mainly connected with students' expertise in autonomous work, with a decrease of teacher's guidance along the succession of the proposed activities.

3.2.3 Pedagogical Content Knowledge in the unit

Pedagogical Content Knowledge (PCK) involved in the unit is related to the analysed physics topics, as well as to its inquiry-based approach. With reference to the domain of physics topics, relevant elements are the following:

- make teachers aware of expected difficulties, misconceptions and/or alternative conceptions in the understanding of the content (as for example “Heat as energy contained in a body”, “Temperature as a measure of heat in a body”, “Different bodies placed in the same environment have different temperatures”, ect.);
- gain ability in using scientific instructional representations (models, mathematical representations,.....) by connecting them and making evident their rationale to fit students' reasoning;
- be aware of students’ learning difficulties in sketching microscopic behaviours;
- connect physics concepts with everyday phenomena;
- relate observation of phenomena with students' representations and models.

With regard to the features of inquiry-based teaching-learning approach, teachers especially need to gain pedagogical content knowledge enabling them to “engage students in asking and answering scientific questions, designing and conducting investigations, collecting and analyzing data, developing explicative models based on evidences, and sharing and discussing their findings” . This mainly involves to make teachers able to:

- provide questions to frame unit and questions for discussion,
- suggest approaches for using technologies as laboratory and cognitive tools,
- suggest approaches for collecting and analysing data,
- support students in designing their own investigation,
- suggest approaches to help students construct explanations based on evidence,
- provide approaches for promoting science communication baseline feature.

3.2.4 Industrial Content Knowledge

The problem of developing effective strategies aimed at reducing heat dispersion in a system is a very actual theme in industry. In fact, the reduction of the effects due to the various processes of heat transfer between objects in thermal contact or in range of radiative influence has a lot of industrial applications, ranging from clothing to building construction, insulation for pipes and aircrafts.

By following the guidelines of ESTABLISH, information are supplied in each subunit about the industrial importance of finding a solution to the proposed problem of thermal insulation. Internet resources, emphasizing the engineering characteristics of insulating materials, are suggested for further development. Moreover, examples are supplied about how conduction, convection, and radiation are considered in choosing materials for buildings and designing a heating system and in explaining how environmental factors such as wind, solar angle, and temperature affect the design and construction of houses.

3.2.5 Assessment

The students were asked to answer a questionnaire both prior to and after all the learning subunits. The questionnaire was suitable prepared and validated by the ESTABLISH team, who slightly differentiated the questionnaire for students attending lower or upper secondary school. The questionnaire consists of several common parts: “My science class”, “My opinions about science and technology”, “What do I think about the following discussions?”, containing items related to students’ experience of science at school, questions about their idea about the impact of science on our society and requests of expressing personal opinions on scientific discussions, where specific aspects of the nature of scientific knowledge were treated.

3.3 The ESTABLISH experience in Sicily: Results from a Guided Inquiry (GI)-based teaching-learning path at secondary school

The unit described in Section 3.2 was first experienced by a selected group of in-service teachers, in terms of a pilot validation, and then administrated to a wide sample of secondary school students. In particular, a sample of 22 teachers, distributed among science teachers at lower secondary schools and physics teachers at upper secondary schools, was selected to be actively involved in the project. The aim of their engagement was first to discuss and validate the unit and then personally guide the experimentation of the teaching-learning unit "A Low Energy House" within the curricular activities of their classrooms. The list of involved schools included five lower secondary (LS) and four upper secondary (US) schools in Sicily, for a total of 216 students (107 and 109, respectively) aged between 15 and 19, with no previous experience in inquiry based learning.

In the wide framework of ESTABLISH experimentation, my personal contribution has been devoted to the second part of the unit experimentation. In particular, my research does not focused on the teachers' work during the validation process of the unit, but on the following implementation of inquiry teaching-learning strategies in the classrooms. In Figure 3.2 we show just two pictures of the activities carried out by the students within the ESTABLISH inquiry-based learning path. Much more information on all the specific activities can be found in short video available at the web page:

http://www.uop-perg.unipa.it/establish/tools.htm (Video ICS Guglielmo II)

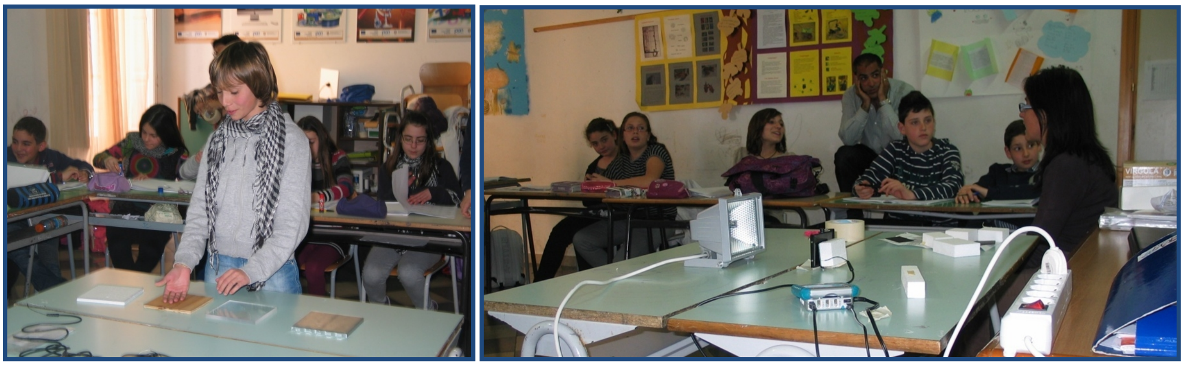


Figure 3.2 Pictures from learning paths experienced within the ESTABLISH Project.

The results of the unit experimentation at secondary school are provided and discussed in the next two subsections. In the first one, explicit attention has been given to the students' outcomes, exploring their perceptions of science as a subject to study at school, their ideas about the usefulness of scientific knowledge in everyday life. The efficacy of a GI-based teaching approach is tested both in terms of motivation to learn and development of nature of science views. The second subsection is instead devoted to analyze teachers' attitudes and perspectives towards the inquiry based approach, as quantified by their responses to a questionnaire specifically developed by ESTABLISH for teachers.

3.3.1 Students’ experience of scientific inquiry through ESTABLISH

The unit has been proposed to all the students involved in ESTABLISH. Some teachers had the opportunity to guide the students through the exploration and scientific investigation of all the problems addressed in the four subsections, while some others focused on specific aspects within one or two subunits, depending on the amount of curricular time the teachers had the possibility to dedicate to the project. However, the results reported in this section refer to those 216 students who were effectively involved in inquiry activities, having the opportunity to deeply experience the spirit of inquiry-based learning, independently of the time spent to explore a given subunit. On average, the students spent about 25 hours to experience the unit.

The ESTABLISH project developed two specific questionnaires to collect the students’ feedback before and after a series of several learning subunits for upper (Questionnaire 2A) and lower (Questionnaire 2B) secondary school, respectively. The two questionnaires are structurally very similar, with the questionnaire 2A containing few questions more and a specific part dedicated to ask opinions about learning and understanding science and some aspects of the nature of science. The results presented below were obtained from the analysis the students’ outcomes to these questionnaires.

Initially, we have extracted all the common issues addressed in the two ESTABLISH questionnaires, in order to draw a direct comparison between the responses provided by the students attending the lower or upper secondary school. After that, we focused our analysis to those specific aspects addressed only in upper secondary school students.

The first part, entitled “My science classes”, is devoted to collect information about the students’ general ideas on science as a subject and usefulness of science and technology in everyday life. The issues addressed in this part are specifically the following:

- School science is a difficult subject.
- School science is interesting.
- School science is rather easy for me to learn.
- I like school science better than most other subjects.
- I think everybody should learn science at school.
- The things that I learn in science at school will be helpful in my everyday life.
- School science has increased my curiosity about things we cannot yet explain.
- School science has increased my appreciation of nature.
- School science has shown me the importance of science for our way of living.
- School science has taught me how to take better care of my health.
- I would like to become a scientist.
- I would like to have as much science as possible at school.
- I would like to get a job in technology.

For each of the above items, the students were asked to express their own opinion by assigning a score in the range 1-4, corresponding to the four-points Likert scale: (1) Disagree, (2) Uncertain-disagree, (3) Uncertain-agree, and (4) Agree. In Figure 3.3 we show the responses provided by the students of lower (top panel) and upper (bottom panel) secondary school. The squares indicate the values averaged over all upper or lower secondary students, while the diamonds are used to connect the 25 and 75 percentiles. Red and green symbols refer to pre-instruction and post-instruction data, respectively.

The analysis of pre-instruction data shows that the LS students generally do not consider science as a difficult subject to learn. Moreover, they believe that science is an interesting matter and everybody should learn it at school, because science knowledge stimulates the curiosity about how the world works and, even more important, it could be useful for our everyday life. However, despite these positive opinions about science, the students seem to do not consider the opportunity to become a scientist as a viable route to their professional career, preferring, with some degree of uncertainty, a job in technology.

Post-instruction results of LS students do not show significant deviations with respect to their pre-instruction views, with only some minor changes suggesting a slightly increase in the awareness of the difficulty of learning science and a little more consideration about the opportunity to get a job in science and technology.

The students attending upper secondary schools answered the same items and their responses are reported in the bottom panel of Figure 3.3. With respect to their younger colleagues, these students show a little greater awareness of the difficulty to learn science concepts and a more uncertain-agree score concerning the interest for scientific knowledge. Despite this, they believe that everybody should learn science at school. Some uncertainty is expressed for what concerns the impact of science in our way of living and health care. Even in these US students, scientific careers are not considered a good opportunity for their future employment, with some uncertainty for technology.

By summarizing the results from “My science classes” survey, we may assert that the GI-based learning path experienced by our students had a relatively modest impact on their perceptions. The students were conscious of the importance of learning science even before the beginning of their ESTABLISH experience and on the potential role science and technology may play in our everyday life. But probably they were missing the connection to some practical examples that could help to consider science so important. In this respect, by engaging the students to personally explore the methods of scientific inquiry applied to the real context of building a low energy house, this learning experience provided the students with a concrete example of how important is the knowledge of science in their everyday life. Moreover, our findings suggest that the students consider school science a different matter with respect to real scientific work. School science is only as a subject to learn, with few practical application to the world around them, as instead in the case of the work made by scientists. The majority of students probably started this experience with the personal convincement that scientists are exceptionally endowed people, as usually considered by common people, and this is the main reason for their concerns about getting

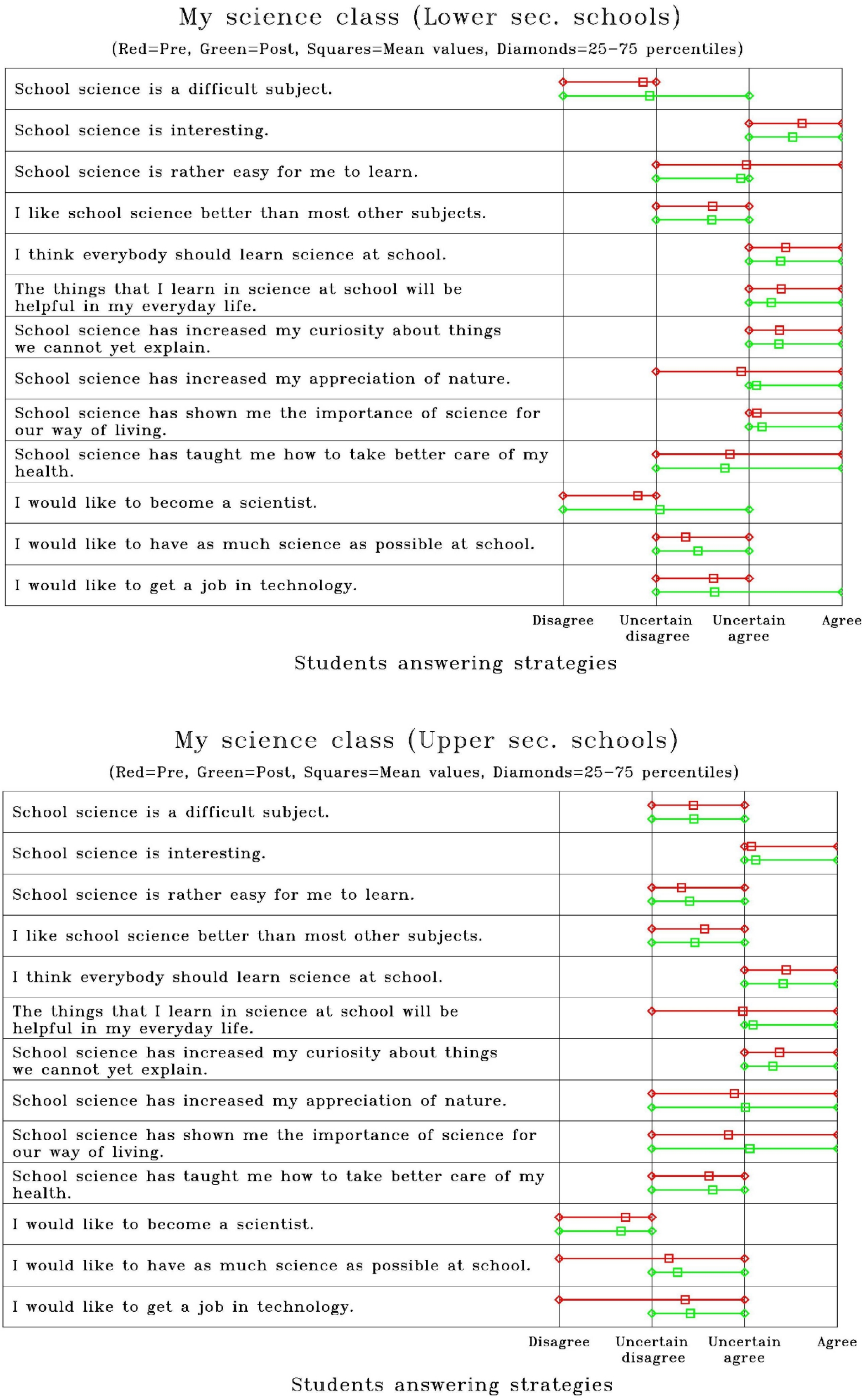


Figure 3.3 Results from the ESTABLISH project in Italy. The topics within "My science class" were selected from the items of questionnaires 2A and 2B of the ESTABLISH tools for the achievement of students' feedback before and after a series of several learning units. Squares indicate the mean values and diamonds the 25th and 75th percentiles.

a job in science. This experience should have helped the students to realize that no difference exists between science at school and the real scientific work, and that scientists are no more than exceptionally curious people, strongly motivated to know and understand how the world works. The lack of interest showed by our students for scientific jobs could be ascribed to a misunderstanding of this point or even to other personal motivations.

The second research issue addressed by mean of the ESTABLISH questionnaires concerns the opinions the students express about science and technology (Figure 3.4), by focusing the following specific social aspects:

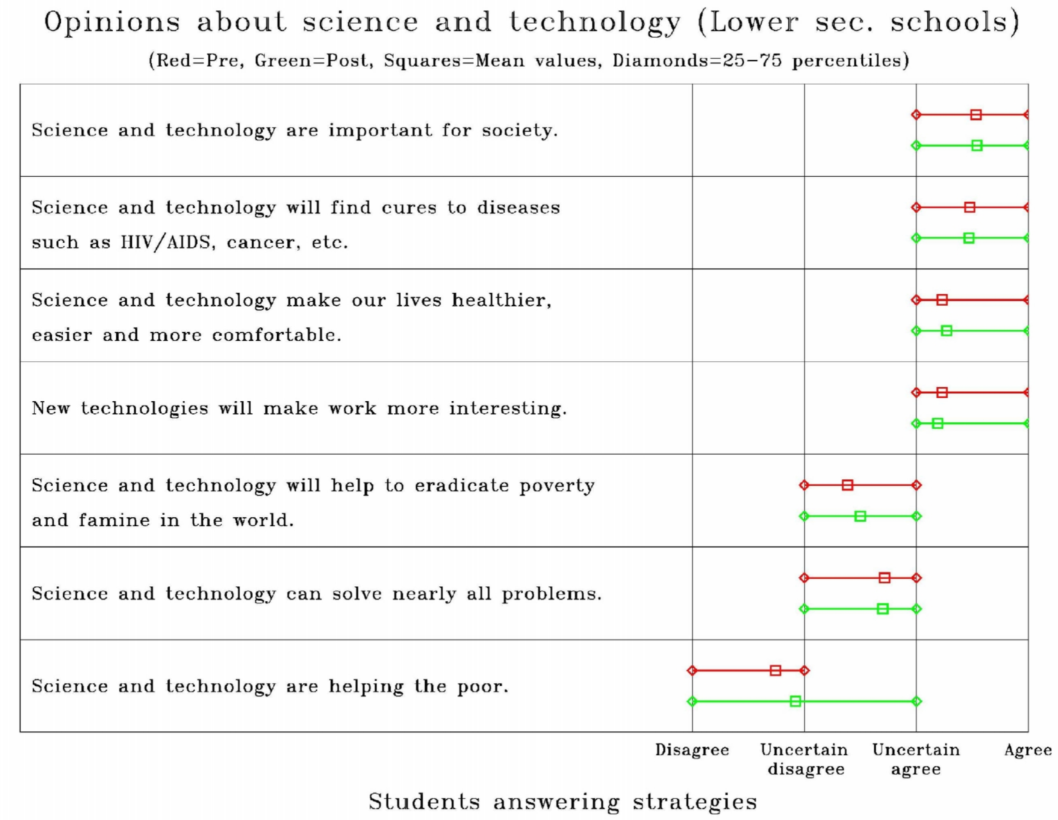
- Science and technology are important for society.
- Science and technology will find cures to diseases such as HIV/AIDS, cancer, etc.
- Science and technology make our lives healthier, easier and more comfortable.
- New technologies will make work more interesting.
- Science and technology will help to eradicate poverty and famine in the world.
- Science and technology can solve nearly all problems.
- Science and technology are helping the poor.

In Figure 3.4 we show the pre/post-instruction results obtained from the responses provided by LS (upper panel) and US (lower panel) students. Even in this case, an overall comparative analysis of pre/post-instruction data shows that our students maintained essentially unchanged their views of social impact of science. Moreover, we find essentially the same outcomes for LS and US students. The students already knew that science and technology are important for society, in particular for what concerns the positive impact of scientific researches in medicine and health care. However, despite these optimistic opinions, both LS and US students show some uncertainty to believe that science and technology can really help to eradicate poverty and/or solve nearly all problems.

A common part of the ESTABLISH 2A-2B questionnaires is entitled “What do I think about the following discussions?” and asks the students to express their agreement or disagreement with one student or the other who disagree about some issue. The proposed discussions focused on the following five specific aspects concerning the NOS:

- Science can be learnt only by studying textbooks, avoiding to follow own experiences.
- Remembering facts is very important to understand science.
- To understand science, the formulas are really the main thing.
- In science, the facts speak for themselves and cannot support multiple theories.
- A theory explaining experimental results cannot change.

The results of the students outcomes are summarized in Table 3.1, where the percentages of students in agreement with the specific statements are reported.



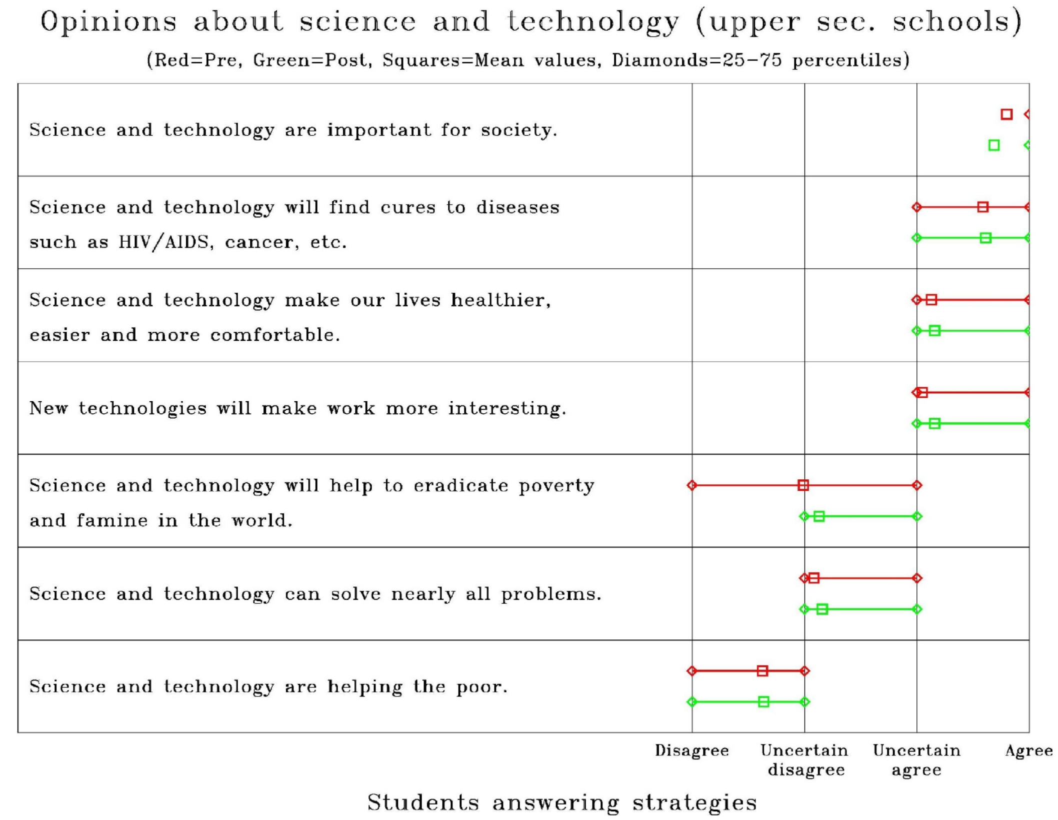


Figure 3.4 Results from the ESTABLISH project in Italy. The topics within "Opinions about science and technology" were selected from the items of questionnaires 2A and 2B of the ESTABLISH tools for the achievement of students' feedback before and after a series of several learning units. Squares indicate the mean values and diamonds the 25th and 75th percentiles.

Table 3.1. Results from LS and US students' responses to the ESTABLISH 2A-2B questionnaires about NOS-related concepts: "What do I think about the following discussions?"

NOS-related concepts	Percentage of agreement			
	LS		US	
	Before	After	Before	After
Science can be learnt only by studying textbooks, avoiding to follow own experiences	73%	64%	52%	31%
Remembering facts is very important to understand science	86%	72%	78%	67%
To understand science, the formulas are really the main thing	77%	61%	85%	62%
In science, the facts speak for themselves and cannot support multiple theories	55%	52%	48%	43%
A theory explaining experimental results cannot change	88%	73%	84%	65%

The ESTABLISH questionnaires focused on those aspects of NOS which are the most commonly observed in students' discussions about science. The fact of considering the textbook as a sacred oracle of absolute truths (the formulas), independently from personal experiences, or a theory as an unchangeable piece of knowledge, or the importance of remembering facts, can be considered as real cognitive obstacles to the learning process. The percentages of agreement to a given NOS concept reported in Table 3.1 represent the percentages of LS or US students who agreed with the idea exposed in that specific statement, respectively before and after experiencing the GI-based learning path. Our pre-activity results show very high percentages, as expected in learners who have never been involved in the practice of science. In particular, high percentages of LS and US students believe that remembering facts is important to understand science. This finding could be symptomatic of an excessively transmissive teaching approach from their instructors. The importance assigned by the students to mathematical formulas in science learning could come from a misleading approach to problem solving, in which more attention is paid to the procedure with respect to the reasoning underlying the resolution process. This finding is more evident in US students' responses, probably because in LS classes the use of mathematics to solve a physics problem is less preferred. Another difference between LS and US pre-instruction students' percentages concerns the relevance of considering the textbook the only source for learning science with respect to personal experiences. In fact, lower percentages of US students who are in agreement with the first statement are found. This is probably because older students are more used to study through multiple resources, such those that can be found on the web and, specifically in the context of learning science, many realistic simulations of physics experiments may provide the students with the awareness of importance of personal experiences in addition to the textbook.

In general, post-activity percentages are all lower than those recorded before the beginning of the project. However, this reduction is barely noticeable in LS students' percentages, while a little more evident in US students' outcomes. In particular, these latter were mostly reduced only in connection with the first, the third and the fifth statements. Globally, our results suggest that secondary school students, engaged in GI-based experiences and without any specific instruction on NOS, experienced modest changes in their views on how scientific knowledge is produced and characterized, confirming what expressed in recent literature at this regard.

A further research question addressed within the context of the ESTABLISH experimentation at secondary school has been focused on the efficacy of a GI-based teaching approach to motivate the students to learn science. Motivation plays a critical role in student learning and achievement, mainly because it is intimately related to the ways students think, feel, and act in schools. Evidence from research on student learning in general (Pintrich, 2003), and mathematics and science in particular (Schoenfeld, 1992), demonstrates that students' motivation, affect, strategies, and beliefs about knowledge in these disciplines can influence their learning and performance. The motivational issue has been already partially investigated by mean of the students' outcomes to the two ESTABLISH questionnaires, in which their opinions about their interest in science were collected. Both LS and US students asserted that school science is interesting and everybody should learn science at school. In order to deepen this aspect, in the context of the unit experimentation the students were asked to express their agreement about the following motivational aspects (selected from Glynn and Koballa, 2006):

- *Intrinsically Motivated Science Learning* (I enjoy learning science; I like science that challenges me; understanding science gives me a sense of accomplishment.)
- *Extrinsically Motivated Science Learning* (I like to do better than the other students on science tests.)
- *Personal Relevance of Learning Science* (I think about how I will use the science I learn; the science I learn has practical value for me.)
- *Self-Determination to Learn Science* (If I am having trouble learning science, I try to figure out why.)
- *Self-Efficacy for Learning Science* (I am confident I will do well on the science tests.)

The students rated these aspects both prior to and after the GI-based experiences of the ESTABLISH unit, by providing a percentage of agreement with the proposed statements. For each statement, the percentages provided by the students were averaged with respect to the total number of LS or US students, respectively. In Table 3.2 the students' outcomes are summarized, by adopting the same format as in Table 3.1.

Table 3.2. LS and US students' percentages of agreement to motivational statements.

Motivation-related aspects	Percentage of agreement			
	LS		US	
	Before	After	Before	After
I enjoy learning science.	79%	84%	52%	81%
I like science that challenges me.	56%	73%	48%	77%
Understanding science gives me a sense of accomplishment.	76%	91%	65%	83%
I like to do better than the other students on science tests.	81%	75%	78%	67%
I think about how I will use the science I learn	38%	78%	41%	73%
The science I learn has practical value for me.	37%	61%	44%	73%
If I am having trouble learning science, I try to figure out why.	68%	72%	62%	79%
I am confident I will do well on the science tests.	56%	77%	48%	62%

From an overall analysis of the percentages provided by the students, it seems evident that they received a positive feedback from the participation to the ESTABLISH project. Even considering that a majority of them, in particular LS students, asserted to enjoy learning science already before the beginning of this experience, the higher percentages recorded both in LS and US students after the GI-based learning path indicate a prominent appreciation of the project. Lower percentages characterize students' pre-instruction answers to the item concerning science as a challenge, probably because they connect this topic to a sort of evaluation of their learning. However, post-instruction data show an increase of these percentages, confirming the benefits of this inquiry approach to intrinsically motivate the students to learn science. Moreover, students report high post-instruction ratings concerning the sense of accomplishment they feel when they understand science. It is interesting to note that the experience of inquiry learning, by stimulating collaborative work, reduces the feeling of competition among students on science tests. The higher increases in students' percentages have been recorded in those two items that address the use and practical value of science learned at school. Finally, this GI-based learning experience seems have stimulated the students to strive further to surmount their difficulties, by achieving a higher sense of confidence to do well on science tests.

In summary, the students' answers highlight a significant result in terms of an increase of their interest and motivation to learn science, but the experienced GI-based learning path does not seem to engage enough the students to effectively impact on their vision of science and on their conceptions about the way scientific work is produced with respect to the science they study at school.

3.3.2 Teachers' perspectives on scientific inquiry through ESTABLISH

The teachers involved in ESTABLISH were asked to answer a questionnaire before the beginning of the project activities. In the questionnaire they ranked as "medium-low" their teaching experience by means of inquiry-based methods. In Figure 3.5 seven items, extracted from the "Classroom Practice/Environment" subsection of the pre-activity questionnaire, were addressed by the teachers, who answered by providing a score between 1 and 5, corresponding to the five-points Likert scale: (1) "Almost never", (2) "Seldom", (3) "Sometimes", (4) "Often", and (5) "Almost always".

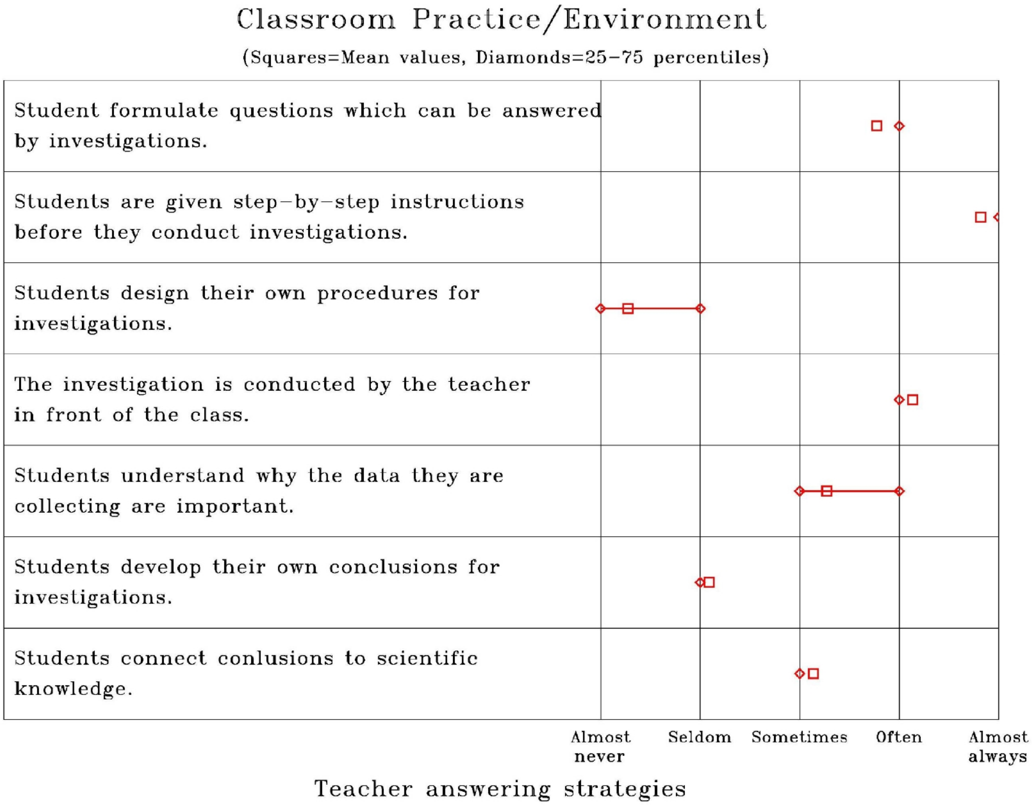


Figure 3.5 Results from the ESTABLISH project in Italy. Seven specific items from the "Classroom Practice/Environment" subsection of the in-service teacher pre-activity survey (ESTABLISH Questionnaire A) are addressed. Squares indicate the mean values and diamonds the 25th and 75th percentiles.

The teachers provided some useful descriptions of their usual practice on teaching science at secondary school and the learning environment of their science classes. In particular, they assert that their students often formulate relevant question that can be answered by performing investigations. However, they always provide step-by-step instructions to their pupils, who are almost never involved in designing the procedure for the carrying out of investigations. The experimental activity is often performed only by the teacher in front of the class, as a merely demonstration of the validity of a physics law. Within this poorly-involving learning environment, the students seem to understand only "sometimes" the reason the teacher is collecting the data or, more in general, the importance of gathering data. As a result, students seldom appear able to draw their own conclusions of investigations. Only "sometimes" the students connect the results from an experiment to scientific knowledge.

In summary, the teachers' responses before their involvement in ESTABLISH clearly highlight an uncomfortable situation within their class learning environment. They appeared to be conscious that a teaching approach based on fruitless demonstrations in laboratory is not the most appropriate one to engage the students and make them active learners.

During the initial phases of the project, the teachers were involved in a training path specifically focused on inquiry teaching strategies, by attending many seminars at university and by gathering information through the ESTABLISH platform, where many web-based resources were available. They also actively participated to the validation process of the teaching-learning unit. After this preparatory period, the teachers experienced the teaching-learning unit, or part of it, with their students, by working-learning in a "renewed" context of their laboratory science class. At the conclusion of their inquiry experience, the teachers feedback was collected by asking them to answer a post-activity questionnaire (ESTABLISH Teacher Questionnaire B), containing almost the same items of the pre-activity questionnaire.

In Figure 3.6 we show the teachers' responses to the items in the "Teacher View of Inquiry" part of the questionnaire. In this survey, the teachers were asked to indicate their level of agreement with each of the proposed statements, by providing a score in the range 1-5, corresponding to the five-points Likert scale: (1) Strongly disagree, (2) Disagree, (3) Uncertain, (4) Agree, and (5) Strongly agree. In figure, the squares indicate the mean values and diamonds the 25th and 75th percentiles. The red and green symbols refers to pre and post-activity data, respectively.

Pre-activity results show a wide range of uncertainty in teachers' responses concerning the understanding of IBSE and the time needed to implement inquiry-based teaching strategies in classroom. Some perplexity is also recorded about the opportunity to definitely use the inquiry approach. However, despite these unclear views, the teachers agree to the statement that addresses the use of inquiry as an appropriate method to achieve the aims of the curriculum. Teachers are generally in disagreement with the statements concerning the lack of understanding of their role in an inquiry classroom and that of the students. They also disagree on defining the inquiry based teaching suitable only for very capable students.

Post-activity data show a better defined situation. After the ESTABLISH experience, the teachers answered the questionnaire by rating a deeper understanding of the meaning of IBSE. The roles of teachers and students are clearer and well identified. More teachers now strongly agree with the statement concerning the use of inquiry to achieve the aims of the curriculum and strongly disagree with those asserting that inquiry methods are only suitable for very capable students or that inquiry will never be his/her main teaching approach. At the end of the GI-based experience, more teachers believed the time needed to implement inquiry methods in classroom no longer as a constrain.

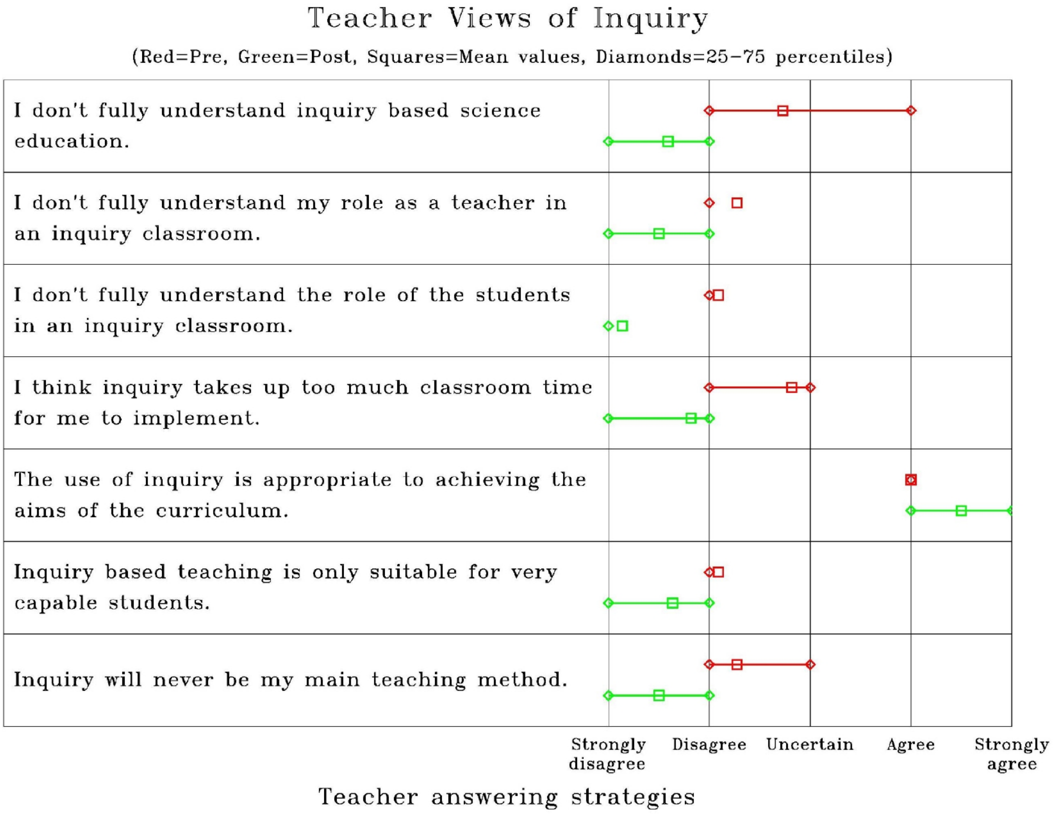


Figure 3.6 Results from the ESTABLISH project in Italy. The topics within "Teacher Views of Inquiry" were selected from the items of in-service teacher questionnaire A(pre) and B(post) of the ESTABLISH tools for the achievement of teacher feedback before and after a series of inquiry learning units. Squares indicate the mean values and diamonds the 25th and 75th percentiles.

The participation to the ESTABLISH project affected our teachers from several points of view. They had the opportunity to spend time to train themselves on inquiry pedagogies, learned how to prepare an inquiry-based teaching unit and personally experienced the benefits of involving the students into the practice of scientific investigations. The changes on the teaching practice induced by the participation to the ESTABLISH project has been investigated by comparing the teachers pre/post-activity responses to the "Teaching Science" section of the ESTABLISH questionnaire. The topics covered in this part of the questionnaire focus on the typical aspects of the teaching practice, as listed in Figure 3.7, where the teachers provided their answers within the usual five-points Likert scale.

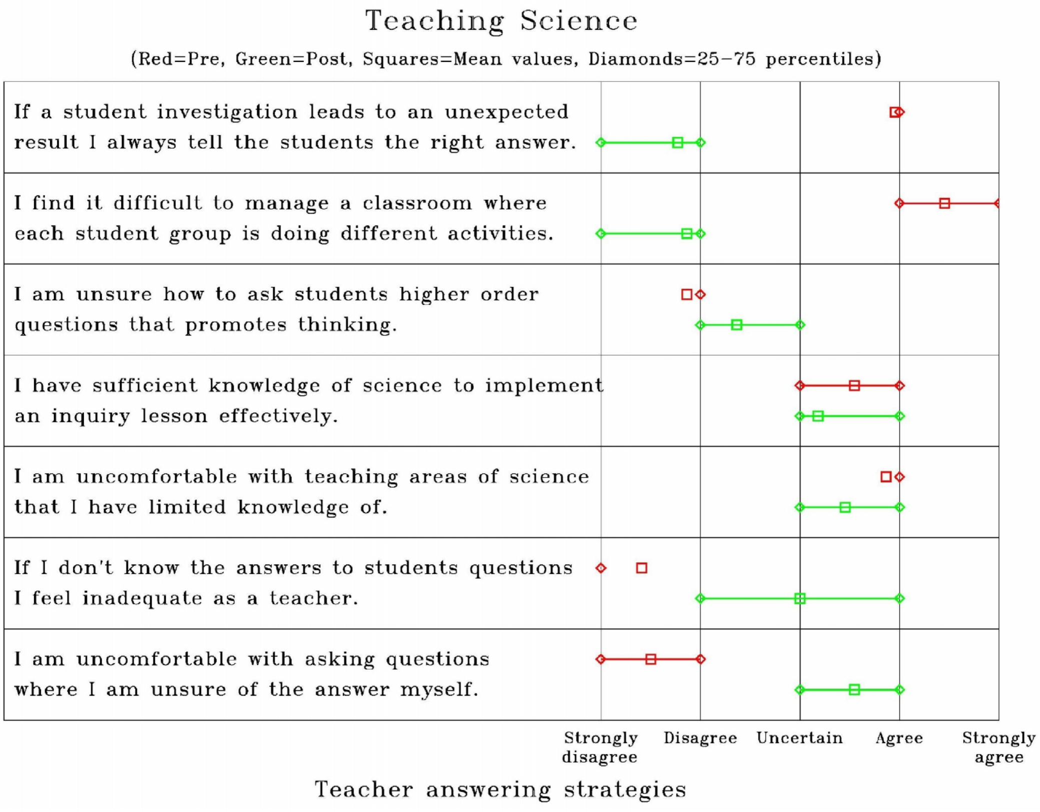


Figure 3.7 Results from the ESTABLISH project in Italy. The topics within “Teaching Science” were selected from the in-service teacher questionnaire A(pre) and B(post) of the ESTABLISH tools for the achievement of teacher feedback before and after a series of several learning units. Squares indicate the mean values and diamonds the 25th and 75th percentiles.

Pre-activity responses highlight some habits in teaching practice that are very common among science teachers. The first one concerns the way teachers face the unexpected results obtained by their students in some experimental activity. Our teachers almost completely agreed on providing the right answer to their pupils. They also agreed on considering difficult the management of a class where the students work in groups, each one performing different tasks. Moreover, they expressed to agree with the unpleasant feeling that teachers may experience when teaching areas of science where they have limited knowledge of. At this regard, however, the teachers strongly disagreed in considering them inadequate as a teacher when they don’t know how to answer to a student question or to ask questions where they are unsure of the answer. On a similar aspect, some uncertain answers were recorded for what concerns the sufficient level of knowledge of science needed to develop the ability to implement an inquiry lesson effectively.

Post-activity results showed marked changes on teachers' responses. This happened, in particular, on the item related to the way the teachers manage unexpected results achieved by the students. Now the teachers seem to be convinced of the importance of letting the students to inquiry and find the right answer to a question or problem by themselves. The ESTABLISH experience had certainly a positive impact on the teachers' view about the different activities the students may fruitfully carry out in groups. Some teachers now are also more convinced to stimulate the students by asking them to answer higher order questions. Uncertain answers still characterize teachers' opinions about the uncomfortable situation of managing students' inquiry on science contents that are not well known by the teachers, who could not be able to answer to the students' questions.

The last part of the questionnaire investigated the teachers' pre post-activity opinions on the "Industrial Content Knowledge" (ICK) within the context of science instruction. In Figure 3.8 we report the average scores of the teachers' answers, within the usual Likert scale, to this part of the questionnaire.

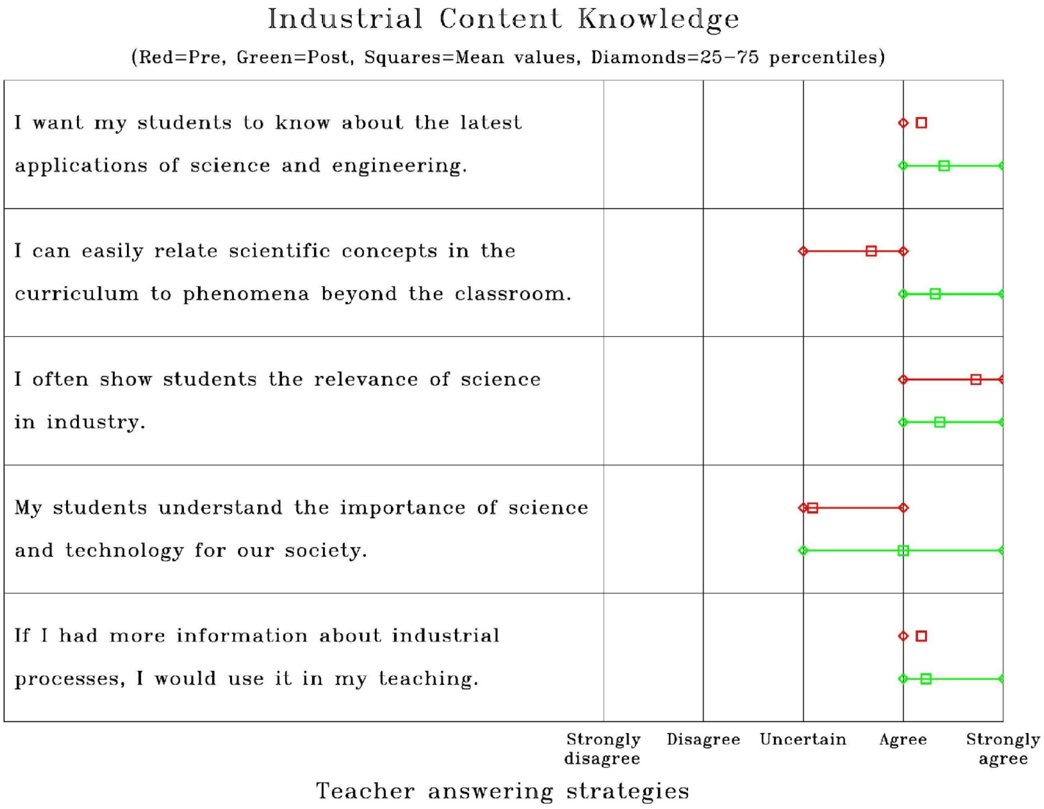


Figure 3.8 Results from the ESTABLISH project in Italy. The topics within "Industrial Content Knowledge" were selected from the in-service teacher questionnaire A(pre) and B(post) of the ESTABLISH tools for the achievement of teacher feedback before and after a series of several learning units. Squares indicate the mean values and diamonds the 25th and 75th percentiles.

Before their involvement in ESTABLISH, the teachers asserted that they were essentially in agreement with considering important to introduce the students to the latest applications of science and technology. In this respect, however, the need of a specific training to update teacher ICK was also reported. Some answers in the range “uncertain-agree” were provided by the teachers on the efficacy of their method of instruction to stimulate the students to understand the links between scientific concepts and phenomena beyond the classroom and the importance of science and technology in our society.

The teachers’ answers collected after the conclusion of the ESTABLISH experience further strengthened this picture. In fact, a greater number of teachers in post-activity responses expressed their strongly agreement with almost all the statements proposed and previously discussed.

In summary, it seems that the participation to the ESTABLISH project had a very positive impact on our teachers. Probably the most striking effect is related to the development of a deeper content knowledge on scientific inquiry. The teachers have firstly acquired the theoretical background of inquiry-based teaching methodologies and the experimentation carried out in their schools has been fundamental to understand how to put scientific inquiry into classroom practice. Essentially, they had the opportunity to explore the efficacy of this “new” teaching method and they have demonstrated to themselves that an inquiry-based approach to teach science at school is not only more involving for the students, by permitting the students to actively participate to the learning process, but also a powerful instrument to introduce the student to the practical applications of science and technology in everyday life. Lastly, the teachers have definitely understood that their concerns about the time needed to implement inquiry in classroom and the additional knowledge required in technological innovations were not motivated, since both aspects can be treated within specific practical training paths.

Chapter 4

Open Inquiry-based Experiences at University

4.1 MISSION TO MARS: A research-based learning environment for engineering undergraduates

This Section addresses the question of the efficacy of an open inquiry approach to define a learning environment in which students may integrate the background of knowledge traditionally received, consolidating tough physics concepts or correcting misconceptions, and also learn how to face and solve real-world problematic situations, using that knowledge in authentic contexts. A sample of thirty engineering undergraduates, having already attended a traditional physics instruction at university, was selected for this study. The students were involved in a six-week long learning experience of open-inquiry based research activities, within the highly motivating context of projecting a thermodynamically efficient space base on Mars. They designed and carried out their own scientific investigations, gathering information, collecting and analyzing data, providing explanations and sharing the results. A questionnaire, containing fifteen open-ended common life problems on thermal science, was administered to the students both prior to and after all activities, with the aim of investigating residual difficulties experienced on problem solving, addressing both student conceptual and epistemological issues. Students' answers were classified into three epistemological profiles and a pre-post instruction comparison was carried out, by using methods of Statistical Implicative Analysis. The students obtained significant benefits from their open-inquiry experiences, both in terms of a more meaningful conceptual understanding of the physics concepts and, from an epistemological perspective, in terms of the strengthening of their abilities to face common life problematic situations.

4.1.1 The research study

In many university courses, physics concepts are still taught by following a traditional approach that aims at transferring the contents and trains the students to solve problems similar to those they will encounter at the final examination. Sometimes, at the end of the lecture cycle, students are also introduced to some laboratory activities, which are often proposed as a mere confirmation of the studied physics laws. Many researches show that this approach is hardly successful because it contains an intrinsic incongruity due to the fact that the problem solving ability, which is almost universally accepted as an evaluation parameter for the students' understanding of concepts, cannot be developed by simply transmitting the rules of the game, i.e. the physics laws governing the natural phenomena, and asking the students to apply them.

With regard to students' understanding of thermal concepts, many researchers have indicated that students can get easily confused primarily because of the language gap between the scientific definition and everyday terminology for heat, temperature and energy (Tiberghien, 1985; Clough & Driver 1986; Kesidou et al., 1995; Meltzer, 2004). Moreover, concepts like specific heat capacity, conductivity or rate of heat energy transfer are sometime not differentiate in student minds and not adequately used in their explanations of everyday phenomena related to thermal concepts (Harrison et al., 1999; Jasien & Oberem, 2002; Streveler et al., 2003). In thermal science, students often have to deal with complex situations, involving emergent processes, such those occurring in systems of randomly interacting constituents. The lack of a relevant mental framework for the understanding of a complex event has suggested the development of schema training strategies (Chi, 2005; Miller et al., 2011), aimed at helping the students to create appropriate mental frames in which to accommodate important science concepts.

Very recently, two powerful instruments, namely the Thermal and Transport Science Concept Inventory (TTCI) by Miller et al. (2011) and the Heat and Energy Concept Inventory (HECI) by Prince et al. (2012), have been finalized to assess the presence of persistent misconceptions in undergraduates studying thermal science. Both researches have confirmed the presence of robust misconceptions in engineering students, even after having attended a semester or more of traditional instruction on thermal science.

This study regards the implementation of an OI-based learning environment, in which already-instructed students are involved in a high challenging research-like work, oriented towards the application of the physics concepts they should have learned in their previous traditional courses on thermal science. To the best of our knowledge, an OI-based approach has never been adopted in the education of engineering undergraduates in context of the study of thermal phenomena. Our general objective is to investigate: (a) the presence of *residual* conceptual and/or epistemological difficulties preventing the effective application of the studied theories to the resolution of problematic situations, which could be encountered in everyday experience and phenomena; (b) the efficacy of an OI-based approach to help engineering students to overcome such difficulties by strengthening their abilities to carry out scientific descriptions and explanations of thermal phenomena.

Our research has been developed in different phases. Firstly, we constructed and validated an instrument having the form of an open-ended questionnaire, with the aim of collecting information about the typical difficulties encountered by young undergraduates. In a subsequent phase, we selected a sample of engineering students and involved them in a pilot project concerning the experimentation of an appropriate OI- learning environment. The students answered the questionnaire before the beginning of the learning activities (pre-test) and again at the end of the learning trail (post-test). The method of implicative statistical analysis has been applied to quantitatively estimate both similarities and implications between different students' answering strategies.

4.1.2 The Sample

Our sample consists of thirty mechanical engineering undergraduates (24 males and 6 females, aged between 20 and 22 years) attending the second or third year of the traditional curriculum of engineering instruction. In order to gain the access to the academic courses, all engineering students passed a multiple-choice test on general knowledge and logic questions with scores greater than 6/10. Our participants were randomly selected between all students having: (i) passed the access test with a score greater than 7/10 and (ii) already attended the basic physics courses and passed the related examinations. In particular, the knowledge background of the selected students included a specific theoretical introduction to the concepts of thermal science and a more technical instruction on applied thermodynamics. The average scores achieved by the students in these subjects are distributed among three levels: low-achieving (6 students with scores in the range: 18÷22/30), medium-achieving (14 students with scores in the range: 23÷26/30), high-achieving (10 students with scores in the range: 27÷30/30). The students' outcomes to their curricular examinations are mainly distributed around the medium-high level, with a global average not far from that recorded in the full population of local engineering students. All selected students accepted to join the project, after a brief presentation made by the authors at the Faculty Council for Mechanical Engineering, where the general objective of the project was illustrated. Students involved in this study have never had specific instruction about the process of scientific inquiry and never participated to other inquiry-based learning programs.

4.1.3 Activity Description: Mission to Mars!

Our decision to activate a pilot project on the topic of thermal physics has been induced mainly by the conviction that the management of many science/engineering problems requires an effective knowledge of the basic concepts of this branch of science. As a consequence, our OI-based learning environment has been designed to meet the students' necessities to achieve a more meaningful understanding of taught physics concepts and improve their abilities to solve common life problems they never encountered before.

The proposed activities involved the students in a highly challenging learning environment, starting from the problem of projecting a thermodynamically efficient space base on Mars. The project was developed across five main phases. During all the stages, the students' activities were supported by two educators having more than fifteen years of expertise in the field of scientific research and on teaching physics at both high-school and university.

In the first phase (Engagement), the educators presented the project to the students, providing a brief description of the context in which their work would have been developed and the motivation for an active participation. The students were invited to take part to an experimental project regarding the best materials to use in the construction and, more specifically, the best design strategies to practice in order to collect as much thermal energy as possible during the Martian day, and avoid heat dispersion during the cold night. Students were asked to work in groups of 5 participants (4 males and 1 female for each group) and to perform scientific investigations devoted to the design, realization and testing of smart devices, having physical characteristics able to maximize the capture and storage of thermal energy from the Sun and/or systems with high insulating efficiency. Group members were chosen by the educators on the basis of student scores on academic physics courses, in order to have the six groups all composed of heterogeneous profiles. All groups of students were invited to carry out their own experimental work, by taking into account the physics underlying the process of thermal energy exchange by conduction, convection and radiation. Before the beginning of all activities, the students answered a questionnaire.

Students dedicated the second phase of the project (Exploration) to acquire information and plan their activities. In this phase, the students were introduced to our laboratory and stimulated to explore the measurement facilities and available materials in order to design their own experiences. They were also informed about the opportunity to use all campus libraries and internet resources to gather appropriate literature. Independently of their membership to a given group, the students followed two different paths of exploration. Some of them started the activity by searching the web to collect information about the physical characteristics of the Martian atmosphere, real weather condition on Mars (for example, the presence of winds), thermal properties of common insulation materials, solar passive systems. Other students ignored the computers and prepared an inventory of all materials in the lab they could have used to carry out their experiments, such as polystyrene boxes, aluminum sheets and pipes, plywood, several plastic materials and glasses. These two different explorative approaches were observed in all groups of students. The educators asked the students to organize in advance their work and to write a document containing the details of all the experiments that they were planning to carry out. However, the educators always left the students free to plan the experiments by following their own procedure and even to bring in the lab home-made resources, or to move outside the department building, if necessary, with the only request of always taking notes of their activities. In this phase the role of the educators was mainly that of a laboratory guide providing, on request, technical support and practical advices on the feasibility of planned experiments.

In the third phase of the project (Explanation), the students carried out their research investigations, designed on the base of their hypotheses pointed out during the explorative phase. They dedicated about thirty hours to complete their laboratory activities by collecting, processing and analyzing data, in the most independent way they were feeling confident to do it. In particular, each group developed one or more devices aimed at testing some relevant physical characteristics of their system (see pictures in Figure 4.1). A group assembled a parabolic mirror with an aluminum pipe on its focus to warm a liquid flowing inside (Figure 4.1a), another group built a scale model of Trombe-Michel wall filled with sodium-polyacrylate gel (Figure 4.1b), others tested several insulating systems (Figure 4.1cdef) and the relevance of the greenhouse effect (Figure 4.1g). A group studied the insulation properties of a modeled underground hypothetical Martian base (Figure 4.1h). In order to collect their data, the students mainly used surface temperature sensors interfaced to a computer for real time measurements, but also infrared thermometers and a spectrometer to evaluate the transmissivity of plastic sheets or glasses. Students used logbooks to note the followed procedures, the difficulties encountered throughout the activity and the changes they made during the inquiry process. The educators supported the students by acting as facilitators of their experimental activities, for example providing tips on software use for a better data visualization. In this phase they often asked the students to question themselves about the scientific motivation of their activities and the obtained results, stimulating the students to reason on the validity of their experiments.

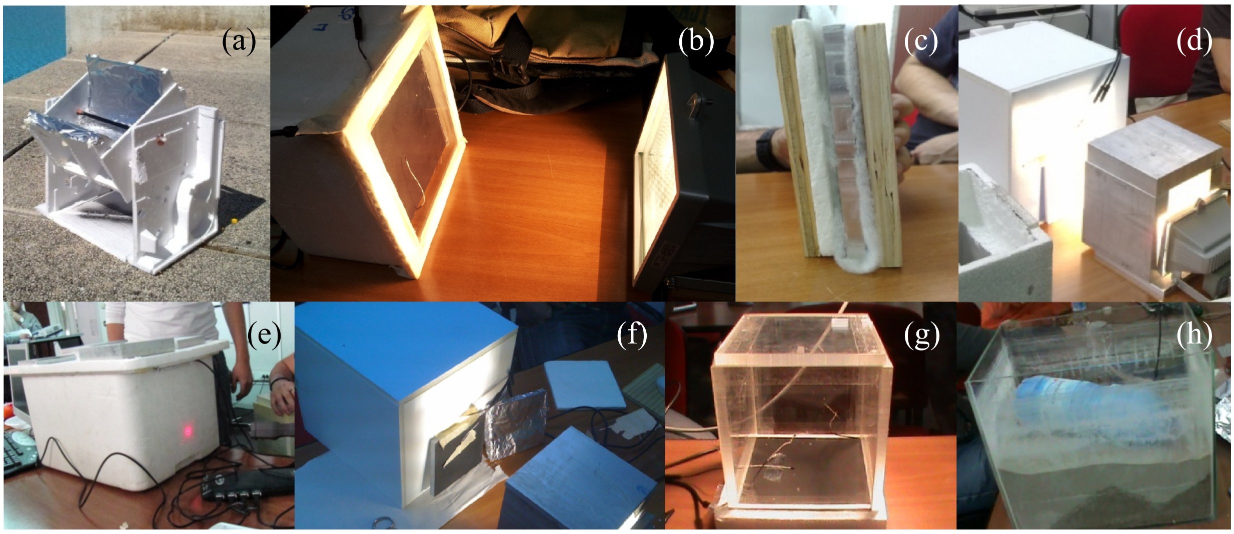


Figure 4.1 Pictures of specific devices assembled by the students during the OI experience: a parabolic mirror (a), a scale model of Trombe-Michel wall (b), insulating systems (cdef), the greenhouse effect (g), a modeled underground hypothetical Martian base (h).

In the subsequent phase of the project, the students presented the most significant findings obtained as a result of their experimental work, by writing a final scientific report (Elaboration). Indeed, the students shared their ideas and preliminary results with the other participants also during the previous phases of the project. However, at the end of all activities, the educators formally invited the students to present the results of their scientific investigations by means of oral communications. In that context, the educators suggested the students to search the web for useful indications on how to prepare scientific reports and presentations.

A final phase (Evaluation) has been devoted to a classroom discussion aimed at comparing and contrasting the results obtained by different groups of students. Here, the educators assumed the role of moderators in student discussions, sometimes by rephrasing unclear discourses in order to focus student attention on a specific concept or by triggering further questions, highlighting critical points on the proposed scientific explanations of their findings. At the end of all activities, the same questionnaire answered at the beginning of the project was re-administered.

4.1.4 Development and Validation of the Questionnaire

Before the beginning of the project, students were not informed about the duty to answer to the same questionnaire both prior to and after instruction, so they answered the test during the first introductory meeting, by considering the questionnaire only as an instrument for educators to assess their initial competences. During the learning activities none of the situations proposed in the questionnaire items has been explicitly analysed. So, we can consider the modifications in the students' post-instruction answers as mainly due to their personal revisions of the involved situations, consequent to the proposed learning activities. Moreover, the students' answers to the questionnaire were all evaluated by the educators only at the end of the project, in order to avoid possible influences on their teaching activity.

All the steps of students' inquiry activities have been recorded directly by students in a work-book (containing planning documents, logbooks of experiments and scientific reports) that students presented at the end of the OI experience. Moreover, the entire activity in laboratory was video-recorded. We collected a huge amount of different data and the process of analysis of all these information is still in progress, on the basis of an in-context search for keywords or phrases and specific aspects of the students' answers that could give evidence of specific cognitive processes.

In this thesis, we report the results of a detailed analysis of pre-instruction answers to the questionnaire and a comparison with post-instruction outcomes. The methods of statistical implicative analysis, presented below in subsection 4.1.5, were applied to quantitatively estimate both similarities and implications between different students' answering strategies.

The questionnaire implementation was carried out by following several stages of development and validation.

Initially, we carefully examined the questionnaires and tests reported in literature, aimed at assessing the student's ability to fully understand thermal concepts and effectively face problematic situations. In particular, we analyzed two recent concept inventories available on the topic of thermal science, namely the TTCI and the HECI (Miller et al., 2011; Prince et al., 2012). Both represent a powerful instrument to investigate students' misconceptions and may provide quantitative evidences of the students' understanding of foremost concepts. However, as any closed-answer questionnaire, a concept inventory provides the learner with a selection of possible answers to a question. Even not considering this as one possible source of bias in students' performance, it certainly affects the students' way to approach the resolution of a problem. Given our specific research questions, we developed an instrument aimed at explicitly investigating the difficulties experienced by engineering students involved into the resolution of common life problems concerning thermal phenomena.

In order to further explore this point and collect information about the typical difficulties encountered by young undergraduates in their learning of thermal science, we informally interviewed twelve faculty professors, teaching physics at engineering. Faculty members, firstly, admitted that the lecture-based teaching approach, commonly adopted because of the high number of students attending the lecture, is not the most appropriate one to receive a feedback from the students about the difficulties experienced during the course. They usually gather some information only at the end of the lecture cycle, through the analysis of the students' outcomes at the final examination, with few exceptions of those who administer intermediate control tests. They also realized that the evaluation of learning difficulties by simply considering the scores achieved by the students on the resolution of standard problems, that most professors usually treat during the lesson, is not effective. In their analysis, faculty members identified several concepts whose full comprehension by engineering students appeared to play a crucial role. They decided to independently rank those concepts, by classifying them within five levels of increasing difficulty. With a percentage of accordance of about 97 %, faculty members agreed that the students usually experience the greatest difficulties when they face new problematic situations where, in particular, the concepts of *heat capacity* and *thermal energy transfer* are involved. Faculties' comments and suggestions were taken into account to prepare a draft version of the questionnaire with fifteen problems, reporting practical experiments or simple real-life situations where the students were asked to make their predictions and provide meaningful explanations.

In the construction of the questionnaire we aimed at evaluating the student reasoning and abilities on pattern recognition, within arrangements of concepts, that has been considered the two main factors affecting a successful approach to the resolution of problematic situations (Ericsson et al., 2006). In this view, our assessment instrument was imagined also as a test to measure the extent to which the students face common life problems by showing a scientific thinking approach. This essentially means a great attention for all the measurable quantities involved in the process and the finding of reasonable connections between the observed phenomenon and an explanatory model, conceived within a continuously evolving matrix of concepts.

In order to assess such ability in students knowledge of thermal science, we decided to structure the questionnaire with open-answer problems, having this format the advantage of collecting the answers that learners give spontaneously, avoiding the bias that may result from suggesting responses to individuals. The majority of the questions, however, were arranged within a multiple-choice structure, containing a mandatory open field to be filled with an exhaustive motivation of the selected choice. In this way, the questionnaire maintained the appearance of a closed-ended test, which is generally faced by the students with a higher level of confidence and more positive attitudes. The analysis of the outcomes from open-ended questions usually needs an extensive coding of the answers; in our case we have performed this action firstly during the process of questionnaire validation, which is described below, and, secondly, with the answers provided by the students selected for this study (see Results subsections).

The validation process of the questionnaire was conducted in three separate phases, each time evaluating the appropriateness, meaningfulness, and usefulness of the specific inferences from the test answers. In the first stage, an 'a-priori' analysis of the questionnaire validity was carried out with the collaboration of three researchers of UNIPA-PERG: each one, independently from the others, tried to hypothesize all possible answers that a student could supply when facing the problematic situations described in the questions. This analysis was conducted independently of the observation (hence the term 'a-priori'), in order to provide a reference point for the subsequent study of the actual students' responses to the questionnaire items ('a-posteriori' data). According to Brousseau (1997), a search for possible student answers and/or answering strategies can be very useful to highlight weak points in the questions, and modify them before administering the questionnaire. The answer lists were compared and discussed by all the researchers, in a form of content validation (Jensen, 2003) and, as a result of this interaction, a revised version of the questionnaire was developed.

In a subsequent phase, a pilot validation was carried out by administering the questionnaire to a group of 45 high school students with no previous experiences on inquiry-based learning and having followed a science curriculum similar to those attended by our engineering undergraduates in their pre-university school career. Students' answers were analyzed by the researchers and compared with those they hypothesized during the a-priori analysis. It emerged that some of the hypothesized answers were not given by the students and, as a contrast, some others, unforeseen during the a-priori analysis, were found. The list of 'a-priori'-collected answers was updated by including the 'a-posteriori' (real students) responses not previously considered. Even if the background on thermal physics was only partially comparable with that of our engineering students, who already attended university level courses, the answers provided by the younger learners were very useful also to highlight residual problems in the questions, mostly due to unclear or ambiguous terminology, and to further revise the questionnaire.

In the last phase of the validation process, we finally administered the questionnaire to a sample of twelve engineering students, in order to test our pilot validation on learners having received the same traditional physics instruction of our research sample, but not being part of it. A focus group was conducted with these students in order to clarify the meaning of some unclear answers they provided and get to the final version of the questionnaire. Most of the answers provided by these students were already included in the list obtained from the previous analysis and few others were added.

In line with previous researches (Fazio & Spagnolo, 2008; Fazio et al., 2012; Fazio et al., 2013), the complete list of answers was used to investigate the student behavior. In particular, the "a priori" analysis, as well as the analysis of real students' answers, made possible to identify three typical answering strategies (see Table 4.1), each one characterized by a different level of efficacy on facing and solving real-context problems. The construction of analytical categories was based on a careful reading of the students' answers by the authors, by using the framework provided by domain-specific expertise and a phenomenographic approach (Marton, 1988; Marton & Booth, 1997; Richardson, 1999).

Table 4.1 Typology of answering strategies of students facing real-life problems.

Practical or Everyday (pe-type)	Descriptive (de-type)	Explicative (ex-type)
The student faces practical physics problems by using only his/her commonsense experience. The answer that he/she provides contain examples from everyday life and, in some cases, physical quantities, which are mentioned but not usefully connected with in each other and do not provide a coherent explanation of the described phenomenon.	*The student approaches the problem resolution by focusing on his/her theoretical background of knowledge, but he/she is not able to find the appropriate connection between the studied theories and the specific context in which the problem is constructed. The answer that he/she provides, always recalls the statement of a physics law or contains one or more mathematical expressions, attempting to give a reasonable description of the observed phenomenon, but without any further step towards the problem resolution.*	*The student approaches the resolution of practical problems by drawing from his/her theoretical background of knowledge, applying the studied theories to the appropriate physical context and achieving a successful explanation of the proposed problem. The answer that he/she provides may contain a textual explanation or a mathematical formulation of the problem; in both cases the problem is well addressed, the most relevant physical quantity involved in the process is identified and a reasonable explicative model is provided.*

The practical or everyday (pe-type) answering strategy is characteristic of a student that, despite the diligence of attending the lecture, remains embedded in the everyday commonsense explanation and does not succeed to transit up to a scientific comprehension of the observed phenomena. The descriptive strategy (de-type) pertains to college level students who generally spend a lot of time studying physics laws and theories, but often in a purely mnemonic formulation, and forcedly biased towards a list of unrelated concepts. The explicative (ex-type) strategy refers to students who achieved a high level of an effective knowledge, which makes them able to search and find explicative models for the resolution of common life scientific problems.

The final version of questionnaire and the complete list of answers collected during the validation phase and the research study, are reported in Appendix A and B, respectively. In Appendix B, each answer is coded by using a five-character code: the first two identify the question number, the third and forth ones refer to the typology of answering strategies, and the last one codes the specific answer given to the question.

As a final step, the authors, independently from each other, associated all collected answers to three 'profiles' characterized by the answering strategies reported in Table 4.1. Discordances between researchers' classification tables were found in some cases, in particular when a student answer was classified by using different strategies or due to different interpretations of students' statements. This happened 8 times when comparing the tables of researchers 1 and 2, 7 times for researchers 1 and 3, 10 times for researchers 1 and 4, 7 times for researchers 2 and 3, 9 times for researchers 2 and 4 and 8 times for researchers 3 and 4. Hence, a good inter-rater reliability of the analysis was found, with a global percentage of accordance of about 98% between the analysis tables of the researchers. The discordances were negotiated in order to get to a unique classification of the student answers (Table 4.2). Each profile can be considered the model of an 'ideal student' answering to all the questionnaire items always demonstrating a given typology of response. These profiles, whose characterizing answers are listed in Table 4.2 by using the same codes reported in Appendix B, have been used for the quantitative analysis of our research data.

Table 4.2. Classification of answers to the questionnaire within the three typologies of Table 4.1

Question	Answers of pe-type	Answers of de-type	Answers of ex-type
1	Q1peA to Q1peE	Q1deA to Q1deE	Q1exA, Q1exB
2	Q2peA to Q2peE	Q2deA to Q2deG	Q2exA to Q2exC
3	Q3peA to Q3peD	Q3deA to Q3deI	Q3exA to Q3exC
4	Q4peA to Q4peD	Q4deA to Q4deH	Q4exA to Q4exC
5	Q5peA to Q5peE	Q5deA to Q5deE	Q5exA to Q5exC

6	Q6peA to Q6peE	Q6deA to Q6deE	Q6exA to Q6exC
7	Q7peA to Q7peG	Q7deA to Q7deF	Q7exA to Q7exC
8	Q8peA, Q8peB	Q8deA to Q8deC	Q8exA, Q8exB
9	Q9peA, Q9peB	Q9deA to Q9deC	Q9exA, Q9exB
10	Qpe10, Q10peB	Q10deA to Q10deD	Q10exA, Q10exB
11	Q11peA, Q11peB	Q11deA	Q11exA
12	Q12peA, Q12peB	Q12deA	Q12exA
13	Q13peA	Q13deA, Q13deB	Q13exA, Q13exB
14	Q14peA	Q14deA to Q14deC	Q14exA, Q14exB
15	Q15peA	Q15deA, Q15deB	Q15exA

4.1.5 Overview of the Statistical Implicative Analysis

In this study, the quantitative analysis of our research sample students' responses to the questionnaire has been carried out by using two functions of Statistical Implicative Analysis: the *similarity* and the *implication indexes*. The system to be considered for this analysis is defined by the combination of both the group of students and all the different answers they provided to the questionnaire. Here, we briefly define the similarity and implication indexes, and give some details about the use we make of them in this research. They are better described in Gras et al. (2008), where a full theoretical discussion of their derivation and meaning is given, and in Fazio et al. (2012, 2013), where applications of their use in specific research contexts are widely discussed.

Lerman's similarity index (Lerman, 1981 ; Lerman et al., 1981) classifies students according to a method of hierarchical clustering (Gordon 1999; Fernàndez & Gòmez, 2008) and it is primarily used to recognize similarities in student behavior (i.e. similar answering strategies). By considering two generic students, labeled as *i* and *j*, the similarity index is defined as follows:

$$s(i,j)=\begin{cases}\dfrac{n_{i\wedge j}-\dfrac{n_i n_j}{n}}{\sqrt{\dfrac{n_i n_j}{n}}} & \text{for } n_i \neq n_j; \quad n_i, n_j \neq 0; \quad n_i, n_j \neq n \\ 1 & \text{for } n_i = n_j\end{cases}$$

where n_i and n_j are the number of answers provided by the students i and j, respectively, n is the total number of different answers, and $n_{i \wedge j}$ is the number of answers that the two students have in common.

If we take into account two generic answering strategies, a and b, we can define the implication index, $q(a,\bar{b})$:

$$q(a,\bar{b}) = \begin{cases} \dfrac{n_{a\wedge\bar{b}} - \dfrac{n_a n_{\bar{b}}}{n}}{\sqrt{\dfrac{n_a n_{\bar{b}}}{n}}} & \text{for } n_a \neq n \ \wedge \ n_b \neq n \quad n_a \neq 0; \quad n_{\bar{b}} \neq 0 \\ 1 & \text{for } n_a = n \ \vee \ n_b = n \end{cases}$$

where n_a is the number of students that put into action the strategy a, $n_{\bar{b}}$ is the number of students not putting into action the strategy b (i.e. using all possible strategies except b), n is the total number of students (30, in our case), and $n_{a\wedge\bar{b}}$ is the number of students using both the strategy a and not using strategy b.

In this thesis, the similarity index $s(i, j)$ is mainly used to detect groupings of student behaviors. In particular, we use it to identify possible clusters of answering strategies with respect to the similarity of students' approaches to solve common life problems in thermal physics (see Table 4.1 and 4.2). The use of ideal profiles of individuals participating in a survey/research is common in many research papers (Rosenberg et al., 2006;Fazio et al., 2012, 2013; Spagnolo, 2006) and the results reported in the literature on this subject validate this method both theoretically and experimentally. The implication index, $q(a,\bar{b})$, allows us to find relationships (or implications) between different answering strategies activated in each questionnaire and to study their coherence in the proposed framework of the multiple approaches adopted to face thermal experiences. The implication index $q(a,\bar{b})$ is able to provide the fine-grain details about implications between the strategies and it is also used to better specify the similarity results.

4.1.6 Results 1/3: Epistemological framework of students' problem-solving strategies

In this subsection we report and analyze the results obtained by administrating the questionnaire to our research sample of engineering undergraduates both prior to and after the accomplishment of the OI-based learning experience. All their answers were independently analyzed by the authors and classified by using the list of responses collected by the researchers during the validation process. A first remarkable finding was the presence of all the answers into the list of responses reported in Appendix B, confirming the robustness of our questionnaire in terms of internal validity and reliability.

This section describes the outcomes from the students within the epistemological perspective of different problem-solving approaches, by mean a similarity-based statistical analysis. We have analyzed the students' outcomes by means of the C.H.I.C. software (Couturier et al., 2004; Markos et al., 2010), which has been used to quantify the similarity relationship between two or more students.

The analysis of C.H.I.C. similarity between real students' answering strategies and those associated to the three ideal students' profiles has been performed separately for each student of the sample. For analysis purpose, we have included in C.H.I.C. input three "ideal students" characterized by a complete coherence in answering the questionnaire by adopting exclusively one of the three strategies mentioned above. A pe-type ideal student always answers the questionnaire items by adopting the practical/everyday strategy reported in the second column of Table 4.2. Similarly, descriptive and explicative ideal students always answer by using the strategies reported in the third and fourth columns of Table 4.2. For each answer to a question, C.H.I.C. associates a real student with one of the three 'ideal profiles' if the student used at least one of the profile-related answering strategies reported in Table 4.1 for that question, as an example, if a student used the strategy Q5exA, Q5exB or Q5exC, he/she is classified as 100% similar (in question 5) to the explicative profile.

In order to investigate the presence of patterns of similarities in students' problem-solving strategies we have compared pre and post-instruction data within the two similarity graphs shown in Figure 4.2. Here, the three squares are the vertexes of an equilateral triangle with side length equal to unity and represent the three epistemological typologies of problem approaching. The distance *d* from each one of these vertexes is related to the similarity index *s* by the relation $d=1-s$. The x and y represent the coordinates in a similarity space where the proximity to a specific vertex implies a high value of similarity with that typology, and vice versa. The concentric circumferences mark the distances 0.25, 0.5, 0.75 and 1 from the vertexes and the black dots represent the students.

Pre-instruction data (Figure 4.2a) confirm the presence of a main cluster of similarity, with respect to the de-type ideal profile and of a less populated one, related to similarity with the ex-type profile. Only the student 5 shows a similarity index that allow us to classify him as mainly similar to the pe-type profile, while the students 10, 26, and 13 are exactly in the middle between the practical/everyday and descriptive typologies. This dual clustering is significantly modified in post-instruction data (Figure 4.2b), where the strong reduction of pe-type similarity (greater distances from practical/everyday vertex) and the significant increase in the number of explicative strategies both contributed to form a dominant ex/de-type cluster of similarity.

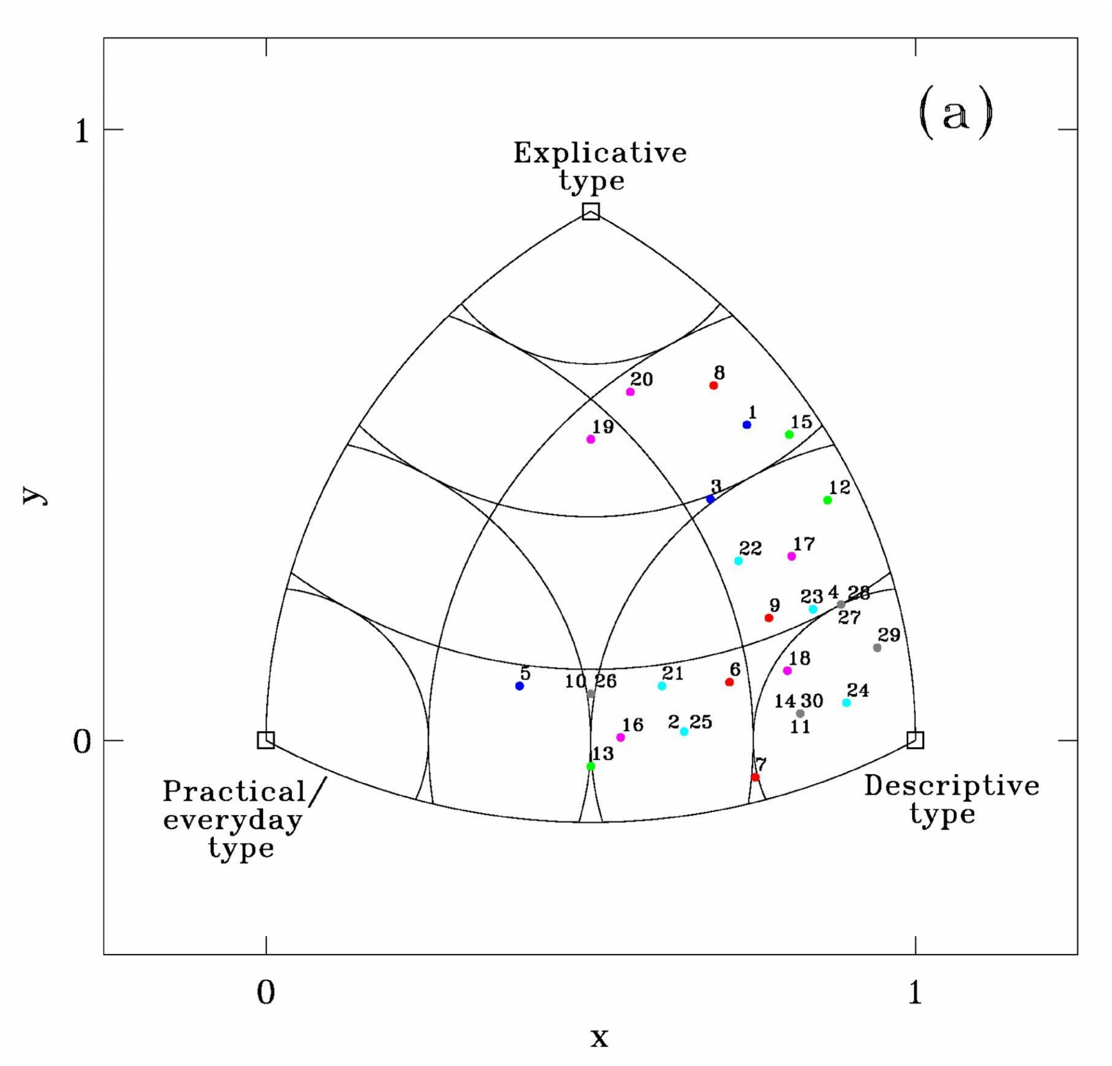


Figure 4.2 (a) Similarity graph for pre-instruction data. The squares indicate the vertexes of an equilateral triangle with side length equal to unity and represent the practical/everyday, descriptive and explicative typologies. The x and y represent the coordinates in the similarity space. The concentric circumferences mark the distances 0.25, 0.5, 0.75 and 1 from the vertexes, the dots and numbers represent the students. Colors are used to identify students who worked within the same group.

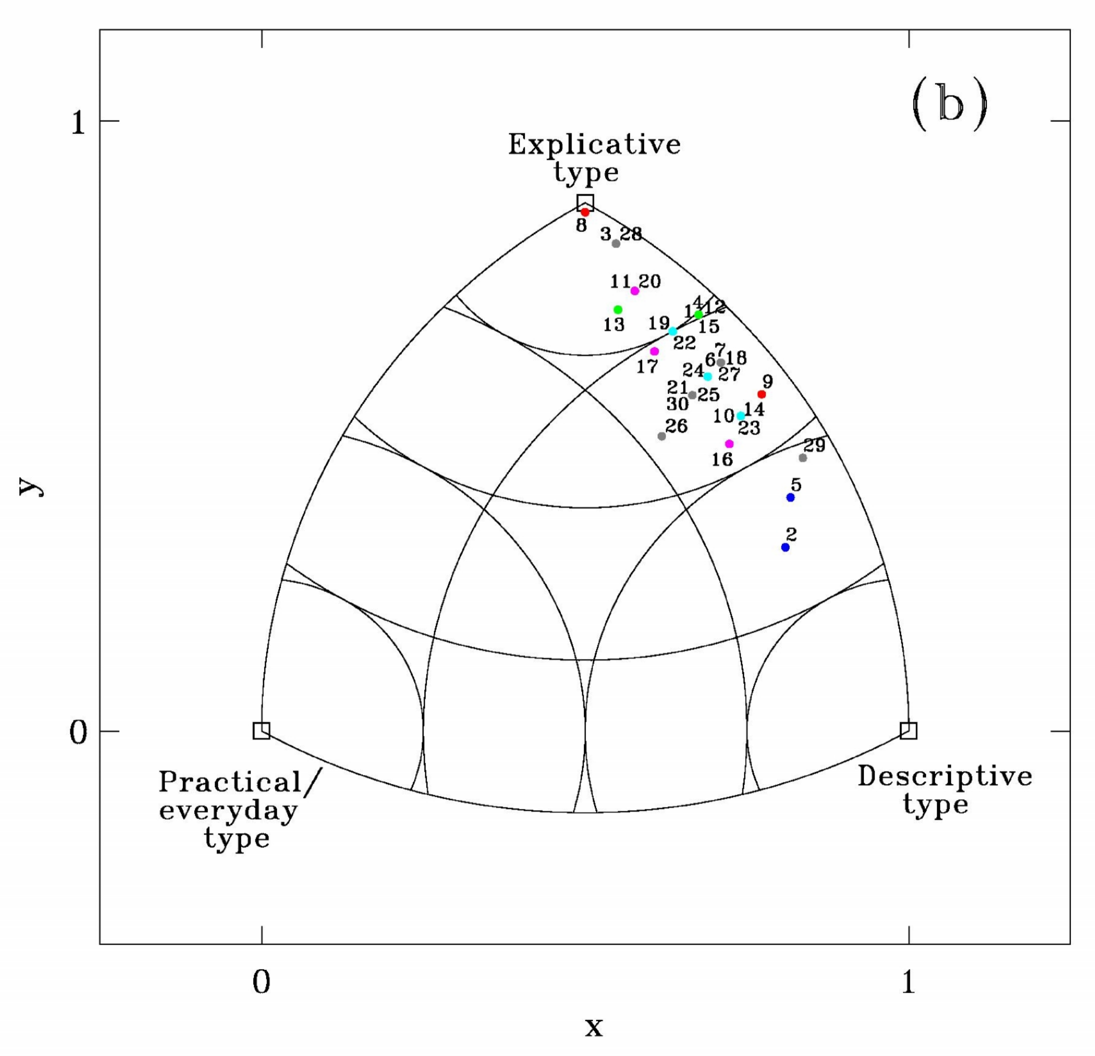


Figure 4.2 (b) Similarity graph for post-instruction data. The squares indicate the vertexes of an equilateral triangle with side length equal to unity and represent the practical/everyday, descriptive and explicative typologies. The x and y represent the coordinates in the similarity space. The concentric circumferences mark the distances 0.25, 0.5, 0.75 and 1 from the vertexes, the dots and numbers represent the students. Colors are used to identify students who worked within the same group.

In both panels of Figure 4.2 the paucity of coloured dots with respect to the expected number (30 students) is only apparent, because several students share the same similarity indexes. This can be observed in Figure 4.3, where the similarity index for all the real students, with respect to the three typologies, are shown. Left and right panels show the pre-instruction and post-instruction data, respectively. Each line in the plot is referred to a specified student, indexed from 1 to 30 on the abscissa, and connects his/her values of similarity index computed with respect to the three ideal student profiles (triangles for pe-type, asterisks for de-type and squares for ex-type). By inspecting the values of similarity index, the following subsamples of students show very close similarity indexes: in pre-instruction data this happens for students' numbers (11-14-30, 27-28-4, 10-26, 2-25), in post-instruction for students' numbers (1-4-12-15, 3-28, 19-22, 6-7-18-27, 21-25-30, 10-14-23, 11-20), respectively.

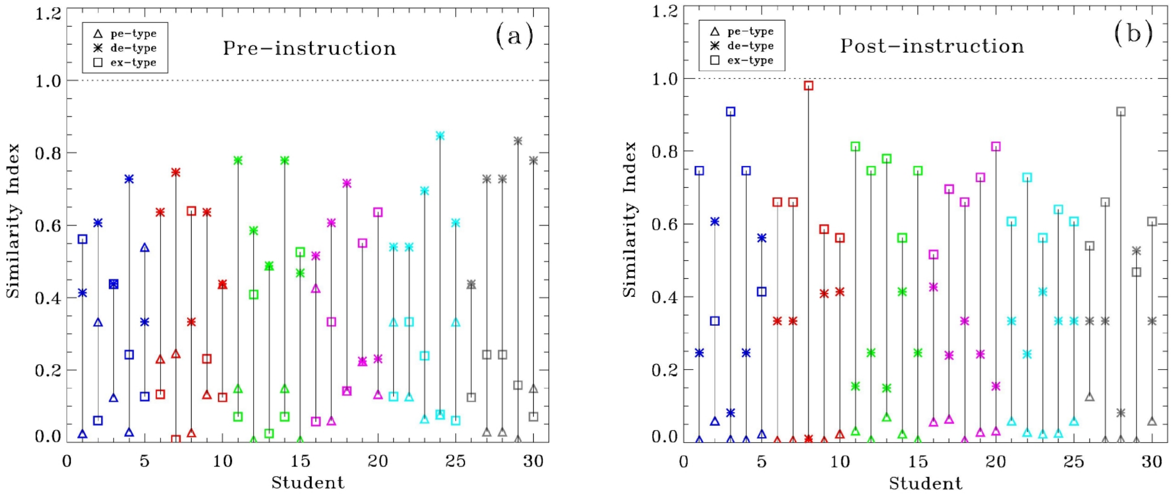


Figure 4.3 Similarity index for each student answering the questionnaire before (left panel) and after (right panel) the carrying out of the OI-based instruction, in relation to the pe-type, de-type and ex-type characteristic profiles. An integer index on the abscissa is associated to each student and used to identify the learner. As in Figure 4.2, colors are used to identify students who worked within the same group.

Pre-instruction data show about ten students approaching the questionnaire by adopting a global solving strategy having a similarity greater than 70% with the de-type. The prevalence of this latter approach is confirmed by an average value of de-type similarity index that settles around 0.6. However, the presence of a less populated sub-sample of 5 students (labeled 1, 8, 15, 19 and 20 in the abscissa of Figure 4.3a) having ex-type similarity indexes between 0.5 and 0.65 is also observed. Surprisingly, for engineering undergraduates already instructed in thermal physics, moderately high values of similarity index associated to the practical/everyday profile are still present in some students. On the other hand, post-instruction data show a better defined situation. In particular, a clear increase of similarity index is observed for the explicative characteristic profile, with the students numbered 3, 8, and 28 reaching similarities greater than 90% and about a 60% average ex-type similarity is globally achieved. A central band of de-type similarity index is observed around 0.35. Significantly lower values of pe-type similarity index are finally recorded.

In Figure 4.3 the students' similarities to the three typologies are plotted by following a specific order that allows an easy recognition of the student's membership to his/her own working group: students labeled 1-5 belong to the first group, 6-10 to the second, 11-15 to the third and so on. Colors are also used to facilitate the identification of a specified group of students. A per-group specific analysis of pre-instruction data shows that the average similarity indexes, separately computed per working group and typology, do not deviate from the global average values of similarity for pe-type, de-type and ex-type by quantities greater than 1.5 σ (standard deviation), confirming the validity of our selection procedure in terms of uniformity of profiles.

The analysis of students' outcomes by mean of both Figures 4.2 and 4.3, this time performed within the context of their own working-group results, shows a general uniformity of similarity levels, with only few exceptions of students having a similarity index exceeding 1.5 σ from the average level of the specific typology, with respect to the other members of their own working group. In pre-instruction data, this happens for students 13, 16 and 26 with high pe-type similarities, students 24 and 26 with high de-type similarities and only for the student 8 with high ex-type similarity. Post-instruction data show all groups performing at almost the same level, with the following noteworthy exceptions: the student 14 with high de-type similarity, the students 8, 22 and 28 with high ex-type similarities, and the students 14, 16 with low ex-type similarities. The students labeled 8, 22 and 28 achieved levels of similarity, with respect to the ex-type, significantly higher than those of their working-group colleagues. However, while we recorded an initial similarity index greater than 0.6 for student 8, suggesting the presence of higher skills even before this experience, this is not certainly the case of students 22 and 28, who initially are merely on the average. On the other hand, the lower post-instruction outcomes recorded in students 14 and 16 could be related to their high pre-instruction values of pe-type similarity. By synthesizing, almost all students performed at about the average levels of pe-type, de-type and ex-type similarity index that characterize their own working group, except for three students outperforming and two students low-performing with respect to the achievements of their colleagues.

An overall analysis of the answering strategies adopted by the students to face and solve the problems proposed by the questionnaire is shown in Figure 4.4. In particular, a comparison between pre and post-instruction data is provided by plotting the percentage of global students' answers as following the classification listed in Table 4.2 within the pe-type, de-type and ex-type profiles.

Pre-instruction data show that more than 50% of students' answers are characterized by a de-type strategy, while about 20 and 25% of students' responses can be classified within the typical approaches of the first and third typology, respectively. On the other hand, the percentages of students' answers collected at the conclusion of the OI experience show the prevalence of the ex-type approach. In fact, an overall enhancing of the occurrence frequency of ex-type answering strategy is observed from pre-instruction to post-instruction data, with a total percentage of students adopting an effective ex-type approach increasing from about 25% up to 63%.

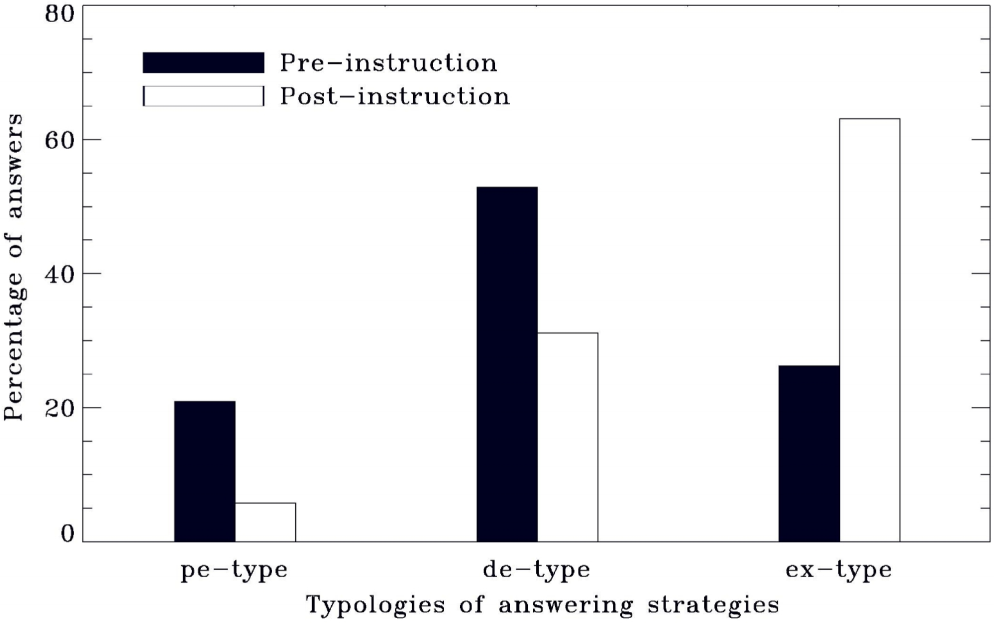


Figure 4.4 Percentage of students' answers adopting strategies characteristic of pe-type, de-type or ex-type profile to answer the questionnaire, administered before (black bars) and after (white bars) participating the OI-based learning experiences.

4.1.7 Results 2/3: Analysis of students' conceptual difficulties

In this subsection we focus on the conceptual difficulties that the students answering the questionnaire still seem to retain, and on the usefulness of OI-based learning experiences to overcome such difficulties. In order to do this, we first list the main features of the questions and briefly comment the students' responses, mentioned by using the labelling system provided in Appendix B.

Question 1: The aim of the first question is to investigate the ability of the student to find the key parameter in the process of solar irradiation of two identical plates. Many students' answers involved the total surface exposed to solar radiation, neglecting to mention the incident angle. Furthermore, two answers showed evidence of a possible misconception connected to the concept of heat, which was considered as a definite quantity contained in a body (Q1peB, Q1deE).

Question 2: The key parameter is the absorption of visible radiation. The aim of this question is to investigate the problems related to the concept of black body, which was often considered only the best absorber, forgetting that it is also the best emitter of thermal radiation (Q2deD and Q3deA).

Question 3: This question deals with the understanding of the process of emission of thermal radiation. Answers Q3deB, Q3deE, Q3deF were strictly connected to the concept of thermal conduction and to the insulation effect obtained by painting the aluminium cylinder. Answer Q3deG showed the presence of a problem related to the identification of the basic mechanism of the cooling process (convection instead of radiation).

Question 4: This question is focused on the concept of specific heat, but many students did not identified this as the right physical quantity involved in the process. Answers Q4deC, Q4deE, Q4deG addressed the understanding of the process in terms of thermal conduction. Answers Q4peA and Q4deH remained focused on the transfer of energy by radiation and on the transmission coefficient. Answer Q4deA took into account insulation effects. Students who answered Q4deB guessed the specific heat as the right physical quantity to be involved in the process, but heat was still considered a quantity to be stored.

Question 5: In connection to the previous question, here the students were asked to explain the physics governing the cooling process of the two bottles, initially warmed at the same temperature. Answer Q5peA involved the transmission of the visible radiation through the water. Convection was taken into account by answer Q5deA, as already found in answer Q3deG. Answers Q5deB, Q5deC addressed the understanding of the process in terms of thermal conduction. Answer Q5deD reported again heat as a storable quantity, as answer Q4deB. Students answering Q5deE supposed the cooling process governed by thermal radiation, by taking into account the sand emissivity.

Question 6: This question regards the melting of two identical ice cubes placed on top of two plates made of the same material and surface, differing only in their thickness. Students would have to predict which one of the two ice cubes melts first. Answer Q6peA relates the heat absorbed by the ice cube with the dimension of the plate (bigger plate means bigger heat available). Answer Q6peB is connected to insulation and answers Q6deA, Q6deB, Q6deC and Q6deD consider thermal conduction through the plates as the key physical process to take into account in order to explain the melting phenomenon described in the test. The Zero Law of Thermodynamics (answer Q6deE) is reported by those students who are convinced that the two ice cubes melt at the same time.

Question 7: Similarly to question 6, here students were asked to investigate how much heat is subtracted from a plate by letting melt an ice cube on top of it. Again, two plates having different thickness are considered. The concept "bigger plate means greater resistance to changes" is at the base of the answer Q7peA. Answer Q7peB is connected to insulation and answers Q7deB, Q7deC and Q7deD consider thermal conduction through the plates. Students answering Q7deE considered the volume of the plate, instead of its mass, as the most relevant quantity.

Question 8: This question asks the students to choice which of two objects (glass made the first and plastic the other) are colder, after a whole night inside a freezer. The aim of inserting this question, despite its simplicity, is to investigate about the resistant misconception "temperature vs. perception of hot and cold" which is typically observed in students at lower grades of education and should be almost completely absent in college level students. Despite this, we still find students' answers Q8peA and Q8peB asserting that the glass cup is colder then the plastic one. Insulation is taken into account in answer Q8deA.

Question 9: This question concerns with the process of thermal conduction and the direction of heat flow. Answers Q9deA and Q9deB focused on the right physical quantity, but without being sufficiently exhaustive. A resistant misconception between temperature and heat is evident in answer Q9deC.

Question 10: Heat capacity is the main topic of this question. In answers Q10peA and Q10peB students considered the volume of an object as the same physical quantity of its mass. The concept of thermal reservoir is considered in answer Q10deB, but the students did not captured the similarity between the hot rock dropped into a pail of water and that in the ocean.

Question 11: The aim of this question is to investigate the student perception of heat exchange by forced convection. The idea of a greater energy exchange is considered by answer Q11deA, but without explicitly citing the physical mechanism involved, as in answer Q11exA.

Question 12: This question concerns with the topic of energy exchange by thermal radiation, by considering the cooling process of a warm object in a vacuum bell jar. Students answering Q12peB and Q12deA, however, considered thermal conduction as the main cooling mechanism.

Question 13: The aim of this question is to investigate how students describe the well known phenomenon of hot air at lower density moving upwards because of natural convection. Answer Q13deA pointed out the presence of a misconception regarding the motion of heat instead of the air.

Question 14: The situation described in this question put the students in front of a typical real-world problem of insulation in the context of a house. The main heat transfer mechanisms involved here are radiation and natural convection. Students answering Q14deA considered the exposition of the higher floor to solar radiation, but they did not write anything about the ground floor. Answer Q14deB takes into account the problem of insulation, but heat was considered again a quantity captured inside a place.

Question 15: This question explicitly treats the practical situation of higher temperatures in rooms at upper floors. As in question 14, the main heat transfer mechanisms involved are radiation and natural convection, but students often "forget" to mention one of the two, as in answer Q15deA (only radiation) or Q15deB (only convection).

The analysis of students' outcomes from the questionnaire allowed the authors to group together those answers highlighting the same conceptual difficulty. This task was carried out by the authors independently from each other, and only as a second step, they crosschecked their groups of students' responses. The inter-rater reliability was very high (97%). Nevertheless, after a clarifying discussion about the few discordances, a global agreement was achieved around five clusters, each one identifying a specific conceptual difficulty. In Table 4.3 we list the clusters, labelled as C1, …C5, of those students' answers which appeared to be associated to a particular detected problem.

Clusters C1 and C2 represent common misconceptions in thermal physics. In particular, cluster C1 puts together the everyday conception of heat as a storable quantity and the exchange between temperature and heat, while C2 focuses on the object dimension instead of its mass in thermal capacity. Clusters C3, C4, and C5 represent students' difficulties in identifying the physical mechanisms involved in the process and/or the appropriate physical quantities to be managed to successfully approach the problem resolution. In these situations the students often already know the concepts, but they get stuck anyhow because of a lack of appropriate epistemological stances.

Table 4.3 Clusters of students' answers highlighting conceptual difficulties

Label	Detected problem on physics concepts	Questionnaire answers
C1	Heat considered as a storable quantity, temperature instead of heat	Q1peB, Q1deE, Q4deB, Q5deD, Q6peA, Q9deC, Q14deB,
C2	Bigger object means greater heat capacity or resistance to change in temperature	Q6peA, Q7peA, Q7deE, Q10peA, Q10peB, Q10deC
C3	Thermal conduction and insulation instead of specific heat or heat capacity	Q4deA, Q4deC, Q4deE, Q4deG, Q6peB, Q6deA, Q6deB, Q6deC, Q7peB, Q7deB, Q7deC, Q7deD, Q8deA
C4	Thermal conduction instead of thermal radiation, thermal radiation instead of specific heat	Q3deB, Q3deE, Q3deF, Q5deA, Q12peB, Q12deA
C5	"Forgetting" to mention thermal radiation or convection	Q14deA, Q15deA, Q15deB

In order to investigate the efficacy of our OI-based learning environment on affecting the relevance of the detected difficulties listed in Table 4.3, we have compared the outcomes from the initial administration of the questionnaire with those obtained at the end of the OI experience. The percentage of students having provided at least one of the questionnaire answers included in the clusters of Table 4.3 is shown in Figure 4.5. Black and white bars represent pre-instruction and post-instruction data, respectively.

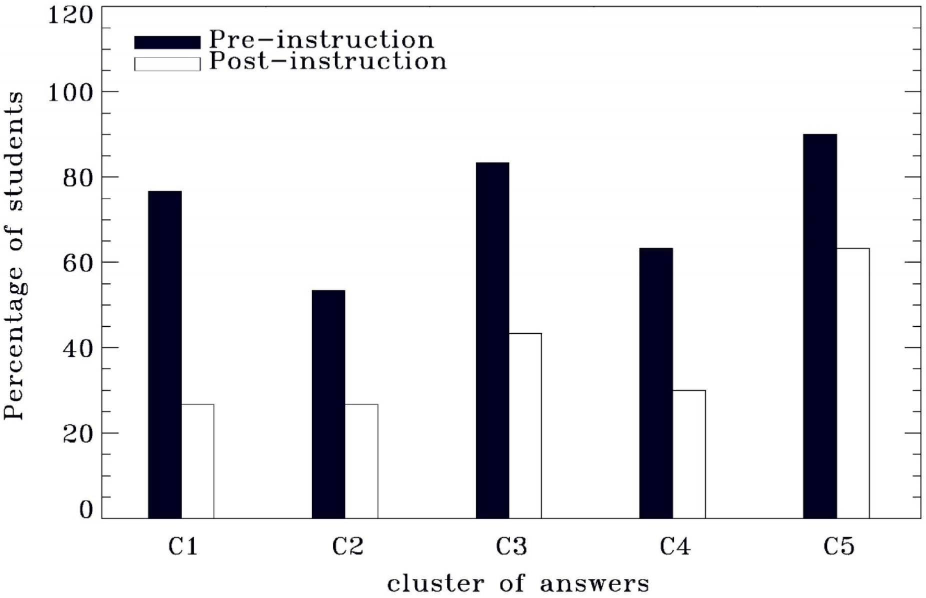


Figure 4.5 Percentage of students having answered to at least one of the questions included in the clusters of Table III. Black and white bars represent pre-instruction and post-instruction data, respectively.

The high percentages observed in the answers collected before the beginning of OI activities show a strong evidence of the presence of students' difficulties, for what concerns, in particular, clusters C1, C3, and C5. At least in one of the answers, more than 75% of students confused heat with internal energy (cluster C1) and showed problems with the understanding of heat in terms of energy transfer between bodies at different temperature. Before starting their OI-based activities, more than 80% of students did not succeeded in solving the practical problems based on the concept of specific heat (cluster C3), and more than 50% was also included in cluster C2, which is related to an exchange of concepts between volume and mass. Clusters C5 is representative of situations in which the students are expected to know the concepts, but they do not provide ("forget to mention") the most complete physical explanation.

Post-instruction data show a marked decrease of the percentage of students providing at least one of the answers included in the clusters of Table 4.3. The most effective reductions are observed in clusters C1, C2, and C4. However, even considering the global trend of reduction as a positive result, percentages greater than 40% are still observed with reference to students that provided at least one answer in clusters C3 and C5. The problem of 'forgetting' to take into account a concurrent transport mechanism of thermal energy in a process, usually convection or thermal radiation, initially observed in more than 80 % of students, appears to be significantly reduced.

4.1.8 Results 3/3: An in-depth analysis of students' responses

In order to deepen the analysis of the students' conceptual difficulties and link these latter to the three problem-solving epistemological profiles discussed above, we used the C.H.I.C. software to identify implicative associations between students' answering strategies. Figure 4.6 shows the implicative graph between some of the answering strategies used by the students before experiencing the OI path. Student's answers are connected each other by means of arrows. For the sake of simplicity, in Figure 4.6 we chose to represent only the answering strategies that imply another one with a significance level of at least 93% (black arrows), 90% (grey arrows) and 87% (light grey arrows). Moreover, in the following we will discuss only implications that involve at least 5 students. We point out that in C.H.I.C. graphs implications have to be read only between pairs of strategies.

Pre-instruction data show interesting implications from the cognitive point of view. Many significant implications shown in Figure 4.6 involve practical/everyday and descriptive strategies and are related to conceptual difficulties. Students showing problematic answers by mentioning thermal insulation effects in answer Q3deE, do the same in answer Q14deB. A similar implication is found between the answer Q8deA and the answers Q9deB and Q7deB, which regard the inappropriate application of the theory of thermal conduction. This latter problem is also a common feature of the implications between the following couples of answers: Q4deC and Q5deC, Q4deE and Q12deA, Q3deB and Q7deC. Students citing the definition of heat as energy in transit (Q9deA), without responding to the practical question, have similar difficulties in applying the Zero Law of thermodynamics (Q7deF). An expected implication, typical of the theory-focused student profile (de-type), is observed in students' answers mentioning the Fourier Law when answering to question 1 with Q1deE and 6 with Q6deD. Implications concerning the lack of a fruitful application of the theories of heat transfer by radiation and conduction are observed between the following couples of answers: Q2deD-Q6deC, Q4peA-Q5peA, Q3deB-Q14deA, Q3deC-Q5deB, and Q3deI-Q13deB. Students answering by following a marked practical/everyday profile bring about implications between answers Q3peC and Q1peB with Q12peB, Q3peA-Q8peA, Q2peC and Q7peF with Q10peA. Some significant implications shown in Figure 4.6, however, regard explicative strategies. In particular, a 93% implication is found between answers Q9exB and Q8exA, which are both classified as explicative type and represent the connection between the clear understanding of the concept of heat flow and that of thermal equilibrium. Another implication involving the ex-type strategy is observed between answers Q8exB and Q9exA, with a percentage of 90%, where students understanding the Zero Law of Thermodynamics and the concept of thermal equilibrium have also a good comprehension of the physics expressed by the II Principle of Thermodynamics. The last ex-type implication regards the answers Q5exA and Q4exA, which are both related to the corrected application of the specific heat concept.

Pre-instruction

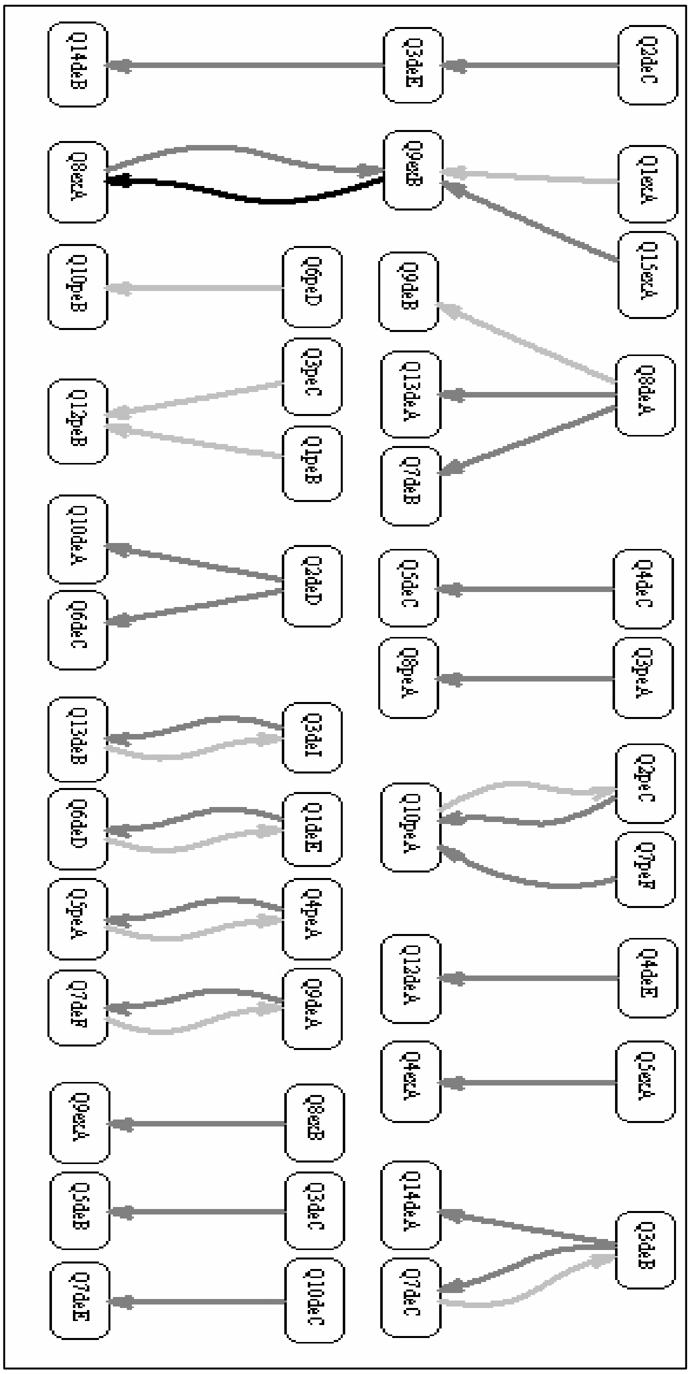


Figure 4.6 Implicative graph for the answers to the questionnaire in pre-instruction administration. Black arrows indicate an incidence of implication greater than 93% between two connected answers. The grey color is used to indicate implications between 90% and 93%; light grey arrows indicate an implication between 87% and 90%. In the upper panel, rectangles represent student answers to the questionnaire as reported and labeled in the Appendix B.

Post-instruction data, shown in Figure 4.7, highlight a significant improvement in terms of the number of implications involving students' answers classified within the explicative ideal profile. These answers do not highlight conceptual difficulties and are, instead, indicators of development of problem-solving skills that use scientific concepts in a appropriate way. In fact, students having achieved the ability to face a practical situation, by identifying the right physical quantity to be managed to solve the problem, will be able to do the same in many different specific contexts. This is the case, for example, of the 93% implications found between answers Q5exC-Q1exB, Q14exB-Q1exB, 90% between answers Q6exC-Q13exB, Q2exC-Q10exB, Q14exA-Q11exA, Q15exA-Q8exA, and 87% between answers Q5exC-Q9exB, Q9exB-Q8exA, Q1exA-Q5exA, and Q3exC-Q6exB. Within the explicative-type strategy, implications having the same physics concept effectively understood are those regarding students' answers Q5exA and Q4exA (specific heat) at 93%, Q4exC and Q6exA (heat capacity) at 90%, Q9exB and Q8exA (heat flow and thermal equilibrium), Q6exA and Q4exC (heat capacity) at 87%.

However, implications involving students' answers within the descriptive strategy are still present, even in post-instruction data. In particular, conceptual problems still highlighted regard the topic of thermal conduction (Q4deE-Q5deB and Q4deC-Q9deA), the concept of thermal power (Q6deC-Q7deA) and the mechanism of energy transfer (Q3deH-Q15deB and Q15deA-Q11deA). These implications can barely be taken into account (as they involve just five students). However they still give evidence of an incidence reduction of the related conceptual difficulties after the OI learning experience. Moreover, in post-instruction data, no implications with significance level greater than 87% between answers of practical/everyday-type are found.

In synthesis, pre-instruction results have shown a direct connection between the pe/de-type epistemological profiles and some physics concepts that the students have certainly studied in their curricular instruction, but without reaching the meaningful knowledge that is necessary to successfully face and solve common life problems on thermal science. These students demonstrated to hold a merely notional knowledge on the concepts of thermal conduction, heat capacity, the Zero Law of thermodynamics, heat as energy in transit, and heat transfer by thermal radiation, with difficulties to proficiently apply them in finding a solution to unexpected situations. This finding means that undergraduates traditionally instructed may still experience residual conceptual difficulties that affect their performances on problem solving, as also highlighted by other researchers (Prince et al., 2012). Post-instruction increase in the number of ex-type implications have clearly shown that students who provided scientifically exhaustive explanations, demonstrating the achievement of high-order problem-solving skills, are able to address a problem by meaningfully applying several physics concepts in a appropriate way.

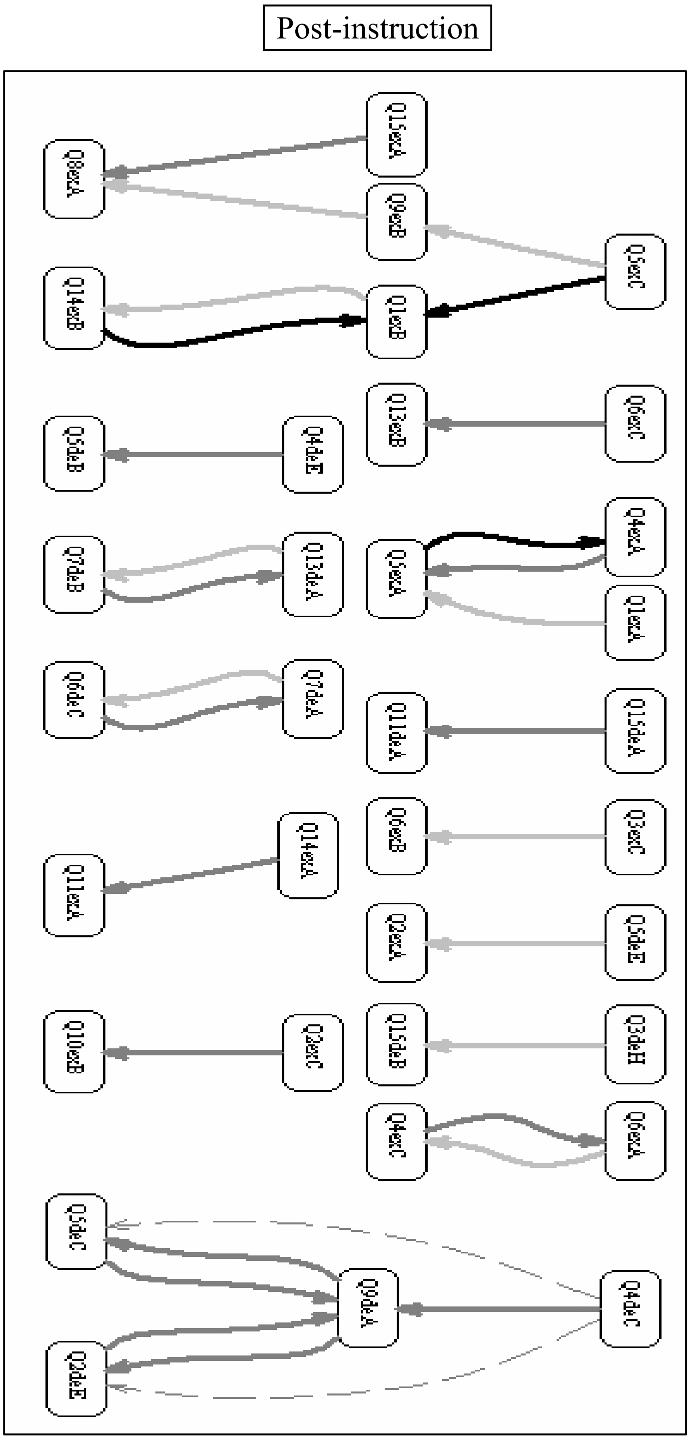


Figure 4.7 Implicative graph for the answers to the questionnaire in post-instruction administration. As in Figure 4.6, black arrows indicate an incidence of implication greater than the 93 % between two connected strategies. The grey color is used to indicate implications between 90 % and 93 %; light grey arrows indicate an implication between 87 % and 90 %. Dashed lines show transitive implications.

4.2 Open Inquiry experienced by high school teachers at university: A deeper view about the physics of thermal radiation phenomena

4.2.1 The rationale of this study

In the past few decades, science education in K-12 grades and up to college and university level, has started to consider a shift from a passive lecture-style teaching to a more active and student-centred teaching strategies (AAAS, 1993; Rocard et al., 2007; NRC, 2012).

Some educational researchers consider GI the most appropriate approach for developing an effective understanding of critical concepts, because it would avoid possible motivational effects that might characterize OI – feelings of inadequacy or frustration due, for example, to achieving of undesirable results – and could affect the successful completion of the learning process (Trautmann et al., 2004; Quintana et al., 2005). On the other hand, having the purest opportunity to act like scientists, students involved in OI activities would gain the awareness of the process of scientific inquiry and a deeper view of the nature of science (Abd-El-Khalick, 2001; Schwartz et al., 2004; Flick & Lederman 2006; Lindsey et al., 2012; Capps & Crawford, 2012). This latter, promoting scientific literacy, is considered a main goal of science education, but also a necessary condition to develop high skills of scientific reasoning.

In this context, a fundamental role is played by the educators. Unfortunately, despite the consensus in educational research on the need of a more student-centred science instruction, many teachers still prefer a lecture-based teaching approach and use laboratory activities mainly to show experimental confirmations of the studied theories to the students. This choice is often driven by personal beliefs about how to effectively teach science, but it may also depend on a lack of knowledge about the proper meaning of inquiry-based instruction. Some teachers, for example, learned as students that the process of doing science can be reduced to a series of procedural steps, such as following the “scientific method”. They associate scientific inquiry to a simple step-by-step procedure, failing to acknowledge the creativity inherent in the scientific process (Bloom & Trumbull, 2008).

Within the context of ESTABLISH, an FP7 European Project aimed at promoting and developing IBSE in European secondary schools, we selected a group of upper secondary school physics teachers without previous experience on research or scientific inquiry and invited them to participate to an OI-based teaching/learning workshop at the Department of Physics and Chemistry, University of Palermo, Italy, on the topic of the energy exchange by thermal radiation. Within the general framework of ESTABLISH - Teacher Education Programme, we provided a sample of selected teachers with the opportunity to perform a specific training in the field of inquiry, with the aim of evaluating the pedagogical effectiveness of such experience to achieve a better understanding of the processes underlying the establishment of scientific knowledge and promote the development of more effective inquiry-based teaching strategies.

Before the beginning of the OI experience the teachers were asked to answer a structured interview, which was designed by the authors with the aim to highlight teachers' beliefs informing their teaching practices. Particular emphasis was given to the pedagogical aspects to be taken into account when introducing new physics concepts and to the educational role of carrying out experimental activities. The teacher answers were analyzed by following a qualitative research methodology (Lindlof & Taylor, 2002).

The OI-based learning path was organized by firstly introducing the teachers to real-life problematic situations within the general context of thermal science. The teachers were invited to focus their questioning activity on the process of energy transfer by thermal radiation, considered one of the most difficult concept to understand for the students. Then, they were asked to design and carry out their own experiments to answer their questions. A scientific investigation on the energy exchange between a powered resistor and its surrounding environment, during the heating and cooling processes, was performed by the teachers. Finally, we asked the teachers to answer again the same questions of the initial interview, also to explore the impact of the proposed inquiry-based teaching/learning path on teachers' conceptions of scientific practices and on the development of new perspectives about the potentiality of inquiry-based teaching methodologies.

The analysis of the teachers' responses to the pre-post interviews pointed out some critical issues regarding the efficacy of a lecture-based teaching approach on the study of thermal radiation and highlighted the development of a new teacher's perspective about the advantages of engaging students in more meaningful inquiry-based activities.

4.2.2 The OI-based teaching/learning workshop

The OI-based teaching/learning path has been carried out by a selected group of five physics teachers, having a traditional background of knowledge on the concepts of thermal science and more than ten years of teaching physics at high school, but no previous experience on inquiry-based teaching. A good knowledge of written English was required, as well as sufficient laboratory skills.

The teachers worked in group as if they were students involved in the study of thermal physics, and, in particular, in the understanding of the tough concepts behind the process of energy exchange by thermal radiation. During all the phases of their OI experience, the teachers' activities were supported by two instructors having more than ten years of expertise in the field of scientific research and on teaching physics at both high-school and university. Written notes about teachers' behaviours and peer discussions were taken by the instructors. This old-fashioned recording method was preferred with respect to the use of videotaping systems, in order to avoid any psychological effect conditioning teachers' activities – teachers could be retained to do or say something because afraid of making mistakes. These notes were useful to the educators in order to reconstruct the learning path followed by the teachers.

The context for OI was created through an initial phase of topic exploration in which the teachers were introduced all together to the general problem of building energy efficient houses, by focusing their attention, in particular, on the design strategies to put in action for achieving efficient solar passive systems. This phase, characterized by teachers questioning on the physics explaining the greenhouse effect, highlighted the presence of misunderstandings about the process of emission and absorption of thermal radiation. Specifically, the teachers inquiring on how fast a body cools by loosing energy exclusively by thermal radiation, did not agree on the role played by the surrounding environment, which could, in some cases, affect the transfer of energy from/to the body. Driven by the need of a deeper understanding of these concepts, the teachers started a discussion aimed at establishing which relevant physical quantities are be taken into account in a contest of a laboratory activity of measurements. The teachers were initially left free to design their own experiments to investigate the cooling process by thermal radiation. Then, they were introduced to the laboratory and invited to adapt their plans on how to conduct their inquiry activity to the available materials and measurement facilities.

4.2.2.1 Step 1: Experience the heating and cooling of a resistor in a vacuum tube

The teachers were invited to start their work by searching the web for technical information and scientific literature, papers reporting experiments on thermal radiation and useful suggestions regarding the definition of an experimental procedure. They noticed that many authors performed experimental studies on the physics of thermal radiation by estimating how the temperature of an object changes as a consequence of the emission of thermal radiation. Some of them (Prasad & Mascarenhas, 1978; O'Sullivan, 1990; Ahmad et al., 2010) used a measurement setup equipped with a lamp consisting of a light bulb with a tungsten filament, whose resistance R is measured for various values of electric power dissipated by the lamp. Resistance information is therefore turned up into the filament temperature T by the R-T relation (Prasad & Mascarenhas, 1978; O'Sullivan, 1990; Ahmad et al., 2010). Other experiments were performed by measuring the surface temperature of a resistor, initially heated and then allowed to cool, inside an evacuated bell jar (Twomey et al., 2009). On the basis of available equipment in laboratory, our teachers decided to prepare an experimental setup similar to that described by Twomey et al. (2009), in which they could measure the temperature of a powered resistor, during the heating and cooling process, inside a vacuum system. However, the teachers decided to realize the vacuum chamber not by using the bell jar, even though available, but a glass tube specifically arranged by themselves for that purpose, mainly driven by the idea of realizing a more manageable system of measurement.

A picture of the experimental setup arranged by the teachers is shown in figure 4.8. The system was mainly composed by a vacuum glass tube containing the resistor and a vacuum pump connected to the tube. The pump was able to lower the pressure inside the tube up to 0.01 bar. The temperature of the resistor was measured by means of a thermocouple which was placed inside the vacuum tube and whose tip was in contact with the resistor surface. Outside the vacuum tube, the thermocouple was connected to an amplifier module and interfaced to a computer. The resistor was ceramic-type, with the following physical characteristics: 6 W, 150 Ω. A power management system was used to drive the electric current into the resistor.

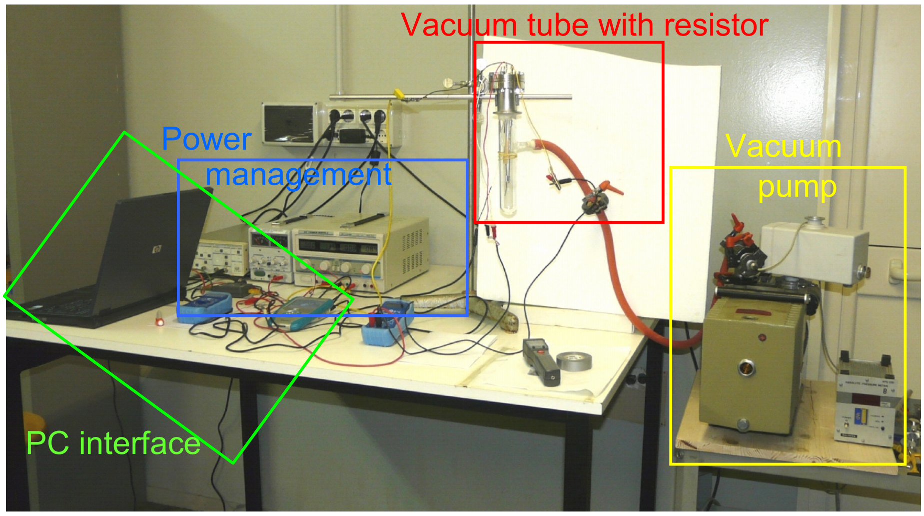


Figure 4.8 Measurement facility for the study of energy exchange by thermal radiation between a heated resistor and its environment.

The first experiment was carried out by measuring the temperature of the resistor during the heating and cooling process. In figure 4.9a we show the experimental data collected by the teachers. The surface temperature of the resistor initially increased very rapidly, until a stationary regime was reached. After about 4000 s, the power driving the current through the resistor was switched off and a subsequent drop of the temperature was observed. Our teachers focused their investigations on this latter phase, concentrating their study on the cooling process of a body emitting thermal radiation.

The teachers discussed about the collected data and agreed on the necessity to carry out a comparison between their experimental findings and the theory of thermal radiation expressed by the Stefan's law:

$$C\frac{\mathrm{d}T}{\mathrm{d}t} = -\varepsilon\sigma S(T^4 - T_\mathrm{b}^4) \qquad (1)$$

where T is the temperature of the emitting object, C the heat capacity, ε the emissivity, σ the Stefan's constant, S the object surface and T_b the temperature of the surrounding ambient. The teachers estimated the heat capacity of the resistor by measuring the slope of the temperature vs. time curve at the initial time of the current switching on, as suggested by Twomey et al.

(2009), finding a value C=1.5 J/K. The emissivity was assumed to be equal to the constant value ε=0.9.

In figure 4.9b we show a comparative analysis of the cooling phase of the resistor. Experimental data (red pluses) are compared with the Stefan's law (red solid line), which was traced by numerically integrating equation (1).

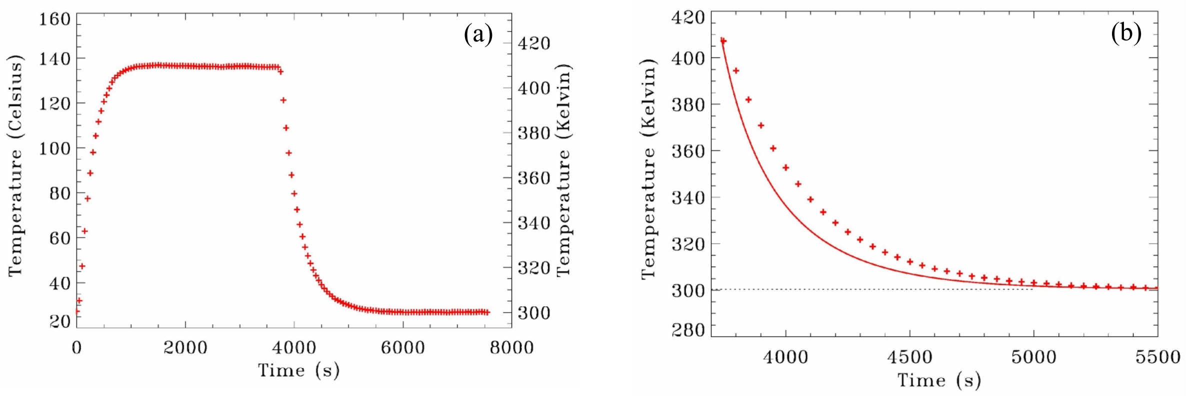


Figure 4.9 (a) Temperature vs. time of the resistor initially heated until the stationary regime and then disconnected from the power source. (b) Analysis of the cooling phase: pluses represent the experimental data; red solid line represents the Stefan's law with constant T_b.

The teachers immediately noted that their experimental data did not meet the theory and started a questioning activity about possible explanations of the observed disagreement. They tried to slightly change the parameters in equation (1), in order to tune the theoretical law and move its curve towards the experimental data, but a satisfactory agreement was not obtained.

4.2.2.2 Step 2: A Deeper view on the physics of thermal radiation

Our OI learning environment was based on data collection via laboratory experiments and research for suitable theories explaining the observations. The mismatch observed in figure 4.9b, between the experimental data and the theoretical curve representing the Stefan's law, stimulated the teachers to perform further investigations.

The teachers firstly repeated their measurements, being convinced that something could have gone wrong during their previous collection. But the new data overlapped almost exactly the old ones. After this check, the teachers started to focus their attention on the theory explaining the energy exchange by thermal radiation. By following the work of Besson (2010), they found that the Stefan's law can also be written in the following form:

$$\frac{t}{\gamma} = -\ln\frac{|\theta - 1|}{|\theta_0 - 1|} + \ln\frac{|\theta + 1|}{|\theta_0 + 1|} + 2(\arctan\theta - \arctan\theta_0) \qquad (2)$$

with $\gamma = C/(4\varepsilon\sigma S T_b^3)$, $\theta = T/T_b$ and $\theta_0 = T_0/T_b$, with T_0 the initial object temperature. The teachers were aware that equation (2) does not represent a solution of equation (1), which cannot be analytically solved. However, the Stefan's law written in this latter form helped the teachers to realize that, under specific conditions investigated below, the last two terms of equation (2) can be neglected and an exponentially time-dependent function for the temperature, i.e. the Newton's law of cooling, can be obtained:

$$T = T_b + (T_0 - T_b)\exp\left(-\frac{t}{\gamma}\right) \tag{3}$$

The teachers immediately tried to match their experimental findings with the simplified Stefan's law, i.e. the exponential curve from equation (3) (blue dashed line in figure 4.10a), and found a significantly better agreement to the data. Being mostly convinced that they were on the right path to solve the mismatch problem, the teachers checked the validity of the used approximation only in a second time.

In order to neglect the last two terms of equation (2) with respect to the first one, the ratio $(T-T_b)/T_b$ has to be 'reasonable' below unity (Twomey et al. 2009; Besson, 2010), which essentially means that the difference between T and T_b has to be significantly lower than T_b, validating the approximation: $(T^4-T_b^4) \approx 4T_b^3(T-T_b)$. The teachers verified this condition by plotting the ratio $(T-T_b)/T_b$ as a function of time (figure 4.10b), by adopting the laboratory ambient temperature as T_b (about 300 K, from figure 4.10a).

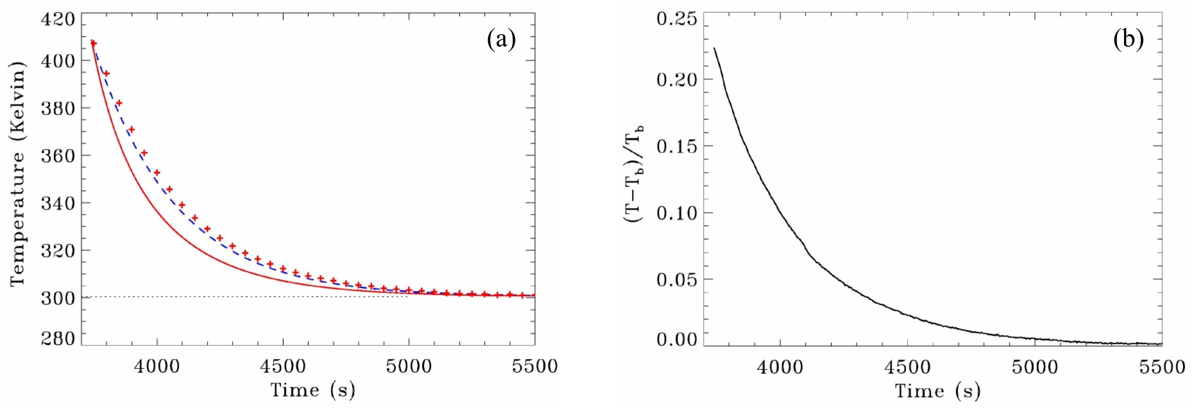


Figure 4.10 (a) Analysis of the cooling phase: pluses represent the experimental data; the red solid line represents the Stefan's law with constant T_b and the blue dashed line shows the exponential approximation of the Stefan's law (Newton's law of cooling). (b) The ratio $(T-T_b)/T_b$ vs. time.

That graph, however, did not settle things once and for all. In fact, instead of being further convincing of the rightness of their hypothesis, it caused in the teachers a general feeling of uncertainty. The question was: "Are the observed values of the ratio $(T-T_b)/T_b$ sufficiently lower than unity?”. The teachers started to discuss, with three of them trying to convince the other two on the exactness of own position and vice versa. No agreement was reached between all the teachers and a further inquiry-based exploration was undertaken.

The teachers realized that the use of a glass tube instead of a bell jar as vacuum chamber was the only difference with similar previously performed experimental trials and focused their investigations on the boundary conditions of their experiment. By discussing about the expression of the Stefan’s law, the teachers observed that the temperature T_b of the environment, surrounding the resistor and also responsible for the quantity of energy absorbed by the resistor from all external sources of thermal radiation, was always considered a constant parameter and equal to the laboratory ambient temperature, as already assumed in similar experiments (Twomey et al. 2009).

In particular, they observed that the glass tube was closer to the resistor than in the case of using a bell jar and, even more important, that the tube, having a lower mass, was characterized by a significantly lower heat capacity. Thinking-aloud reasoning about these findings brought the teachers to suppose that the temperature of the glass tube containing the resistor could greatly enhance its value during the experiment and affect the results.

The teachers firstly checked their hypothesis by using an infrared thermometer, and found that the temperature of the glass tube actually rose significantly during the experiment. For this reason, they decided to repeat their previous measurement, by tracking, at the same time, both the surface temperature of the resistor and that of the vacuum tube. The results of this second experiment are shown in figure 4.11a, in which the teachers plotted the temperature of the resistor (red) and the temperature of the surrounding environment (green) vs. time.

The teachers obtained the quantitative estimate of the temperature increase of the glass tube as a function of time and confirmed that the assumption of considering constant the temperature of the environment surrounding the resistor was not valid in their experiment.

At this point, the teachers returned to the theory of thermal radiation and started to think on how to modify it in order to take into account the effect of a changing ambient temperature. They decided to numerically integrate the Stefan’s law, equation (1), by including in the computation the measured values of T_b, changing in time as experimentally observed (green pluses in figure 4.11a). The comparison between the temperature of the cooling resistor (red pluses) and the “updated” Stefan’s law (black solid line), modified by considering a variable surrounding ambient temperature, is shown in figure 4.11b. The black curve, calculated by considering this “new” theory, is significantly higher than that traced by the Stefan’s law with the usual approximation of a constant ambient temperature (red line in figure 4.11b) and now it matches the data. The almost perfect correspondence between the experimental findings and the theory secured the agreement between all the teachers and finally convinced them to reject the previous hypothesis of a cooling process following the Newton’s law in favour of the original Stefan’s law.

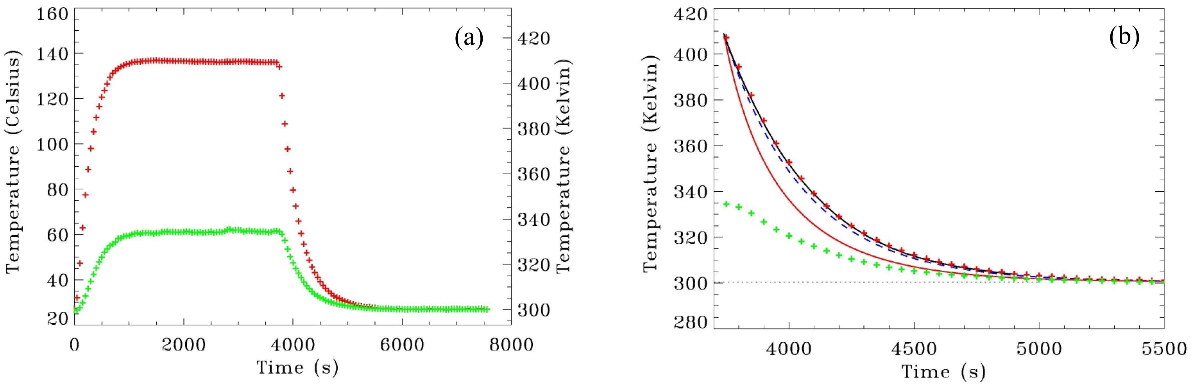


Figure 4.11 (a) Comparison between the temperature of the resistor (red pluses) during the heating and cooling process and the temperature of the external surface of the vacuum tube (green pluses). (b) Analysis of the cooling process: plus symbol is used to represent the experimental data (red is used for the resistor and green for the environment); red line shows the Stefan's law with constant T_b; the blue dashed line indicates the exponential approximation of the Stefan's law and the black line shows the numerical solution of the Stefan's law, with the inclusion of a changing temperature of the surrounding environment.

4.2.2.3 Step 3: The vacuum tube placed in a water bath

In order to further check the hypothesis of an influence of the ambient temperature change on the cooling process of an object emitting thermal radiation, the teachers decided to carry out a third experiment. They repeated the previous measurement by trying to maintain an almost constant ambient temperature around the resistor. In order to achieve this, they placed the vacuum glass tube in a water bath, which would play the role of a thermostat. Our teachers immerged the glass tube inside an aquarium tank containing about 40 litres of water at ambient temperature, as shown in figure 4.12a. The results of this experiment are plotted in figure 4.12b.

The cooling of the resistor inside the vacuum tube immerged in a bath of water at ambient temperature, took place with its surrounding being maintained at an almost constant temperature, due to the great heat capacity and convective efficiency of the water. In fact, in figure 4.12b we can see that the surface temperature of the glass tube (green pluses) remained almost constant around 300 K, rising of about few degrees only in the warmest phase of the experiment. The surface temperature of the resistor (red pluses) now decreases as a time-dependent function following almost exactly the Stefan's fourth-power law of thermal emission (red line).

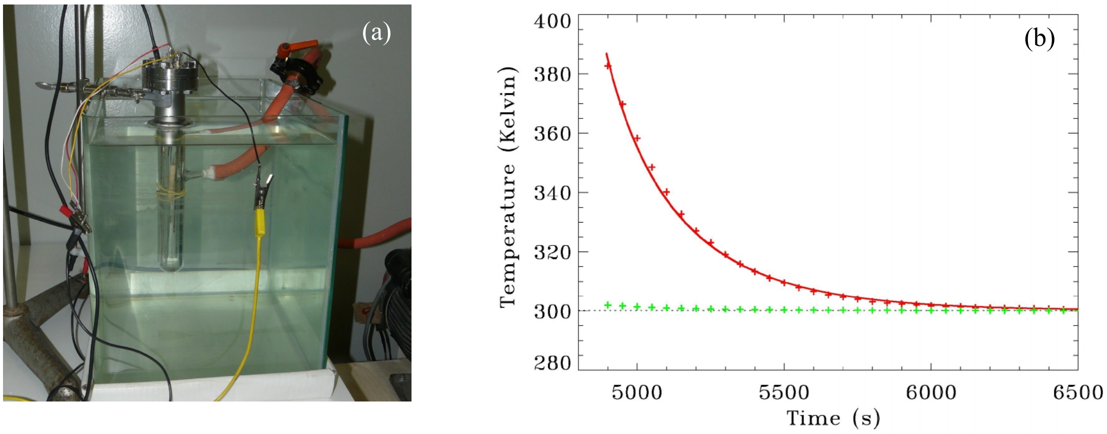


Figure 4.12 (a) Experimental setup with the vacuum tube immerged in a bath of water at ambient temperature. (b) Analysis of the cooling process: plus symbol is used to represent the experimental data (red is used for the resistor and green for the glass tube); the solid red line shows the Stefan's law.

The cooling of the resistor inside the vacuum tube immerged in a bath of water at ambient temperature, took place with its surrounding being maintained at an almost constant temperature, due to the great heat capacity and convective efficiency of the water. In fact, in figure 4.12b we can see that the surface temperature of the glass tube (green pluses) remained almost constant around 300 K, rising of about few degrees only in the warmest phase of the experiment. The surface temperature of the resistor (red pluses) now decreases as a time-dependent function following almost exactly the Stefan's fourth-power law of thermal emission (red line).

The underwater vacuum experiment showed an agreement between the experimental findings and the "recovered" Stefan's theory. This firmly convinced the teachers on the validity of their hypothesis regarding the dominant role of the environment surrounding objects, which emit heat radiation but, at the same time, receive thermal energy from all the outside thermal sources.

4.2.2.4 Step 4: Radiative cooling of a resistor inside a bell jar

Being convinced of the importance of their findings, the teachers decided to carry out the last two experiments by changing their measurement setup, dismounting the glass tube and arranging the vacuum chamber by using a bell jar (see figure 4.13a). The aim of performing these measurements was to investigate the effects of the ambient temperature change, if any, on the radiative cooling of a resistor placed in an evacuated bell jar, which constitutes the vacuum arrangement traditionally adopted in similar experiments.

The teachers recorded at the same time both the surface temperature of the resistor (red pluses in Fig. 4.13b) and that of the bell jar (green pluses). In figure 4.13b the decreasing trend of the resistor temperature is compared with the Stefan's law numerically integrated by assuming a constant value for T_b (equal to the laboratory ambient temperature - red line), and with the Stefan's law integrated by including a T_b changing as experimentally observed on the surface of the bell jar (black line). In this experiment the teachers found that the temperature of the bell jar did not significantly depart from the laboratory ambient temperature and they explained this finding mainly by considering the increased heat capacity of the bell jar with respect to the glass tube. As a consequence, little differences are present between the Stefan's law with constant T_b (red line) and that with a variable T_b (black line). As in the case of the underwater experiment (subsection 2.3), the experimental data are well described by the theory of thermal emission even without taking into account a change on T_b.

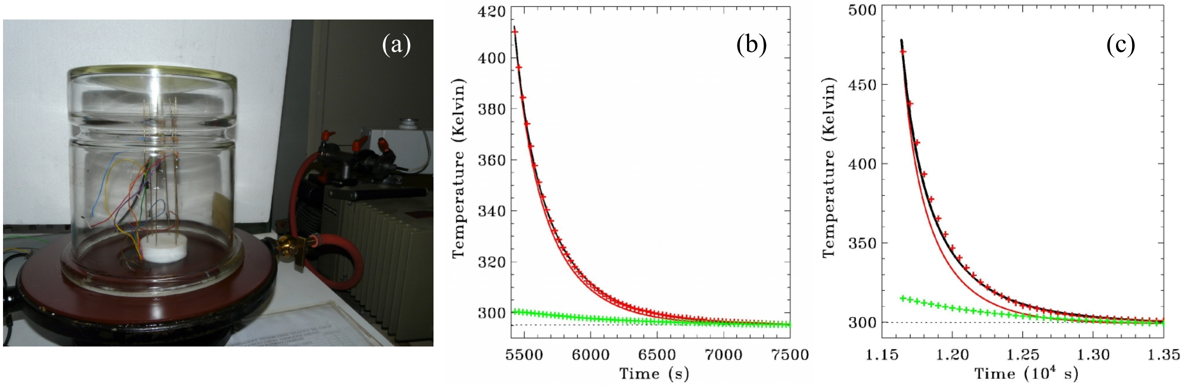


Figure 4.13 (a) Experimental setup with the resistor placed inside an evacuated bell jar. (b) Analysis of the cooling process: plus symbol is used to represent the experimental data (red is used for the resistor and green for the glass tube); the red line shows the Stefan's law with Tb equal to the laboratory ambient temperature and the black line the Stefan's law with Tb changing as measured on the bell jar surface. (c) Cooling process by using a more powerful resistor and an aluminium-coated bell jar.

The results obtained from this experiment convinced the teachers about the validity of many similar investigations reported in previously published researches and provided a solid understanding of the reason for which such studies had never included the effect of a changing ambient temperature in their analysis of an object cooling by thermal radiation.

Finally, the teachers decided to carry out the last experiment, in which they maximized the energy emitted by the resistor, trying to increase the bell jar temperature and observe, even in this case, a departure of the data from the Stefan's law with constant T_b. In order to achieve this target, the teachers replaced the resistor with a more powerful one (12 W, 150 Ω). They also used the expedient to coat the bell jar with an aluminium foil, with the aim of containing the heat loss from the bell jar by thermal radiation. The results of this experiment are shown in figure 4.13c.

The increase of the bell jar temperature (green pluses in figure 4.13c) with respect to the laboratory ambient temperature was about three times the value measured in the previous experiment (figure 4.13b). One more time, the data did not follow the Stefan's law with constant ambient temperature (red line in figure 4.13c), but they were better described by the Stefan's law computed by taking into account the changing Tb (black line in figure 4.13c).

Even if a satisfactory agreement between data and theory was reached, the teachers observed that the black curve in figure 4.13c does not perfectly match the measured resistor temperature, which remains a little bit higher in the warmest part of the cooling phase and lower in the coldest part, with respect to theoretical prediction. The teachers finally discussed about which factors could have played a role into the process and they motivated the observed little mismatch as probably due to having measured the external surface temperature of the bell jar, whose thickness cannot be neglected and a gradient of the temperature would had to be taken into account.

4.2.3 Inquiry-based pedagogies: The teachers' perspectives

All the selected teachers have a degree on mathematical sciences and received a traditional lecture-based physics instruction at university, where they attended only some purely-demonstrative laboratory courses. As a matter of fact, our teachers have never been actively involved in a physics laboratory at university before this experience. At the beginning of their enrollment into the Establish project, they answered a questionnaire, which was administered to a much wider sample of European teachers, in order to collect average information on teachers' attitudes and views towards science and teaching science, classroom practice/environment, knowledge about IBSE methodologies. Our teachers' responses to the questionnaire clearly stated that before being involved in this OI-based path on thermal radiation, they mainly ignored the significance of carrying out activities in the context of scientific inquiry.

Both prior to and after their OI experience on thermal radiation, the teachers were asked to individually answer a structured interview, conducted by one of the researchers face to face with the teacher. The answers were audio recorded and then discussed and analyzed by the three authors. The questions and the transcripts of the teacher answers, following a pre and post-activity format, are reported in the Appendix C, where the teachers are identified by letters a, b, c, d & e.

From teacher answers to the pre-activity interview, concerning the role of experimental activities (see questions 1 & 2 in Appendix C), it appears evident that in their past teaching practice they have always carried out laboratory experiments aiming at verifying the physics laws already presented to the students, who are often considered an "audience". The only noticeable exceptions are teachers labeled b and e, who in their answers explicitly mention the need for an engagement of the students and the importance of cooperative work. Our teachers were used to always prepare in advance the experiment they were going to propose to the students. The main reasons given include the need to let the students check the laboratory materials/facilities, to train them to perform step-by-step all the measurements and calculations needed, in order to check for the achievement of the expected results, and to ensure the success of the demonstration of the studied physics law in front of the students. Moreover, teachers usually never started an experimental project by searching the literature or thinking about how to arrange the experimental setup, because they always followed the textbook indications.

In their post-activity answers, the teachers highlighted the importance the experimental work in laboratory may have in order to deepen the students' conceptual knowledge and improve their reasoning skills. In particular, the answers provided by the teachers to question 1, concerning the educational role of experimental activities, attest the change of their view about the aim of a physics experiment, which comes to be considered a powerful teaching instrument to stimulate the student to experience the world with critical thinking and strengthen scientific reasoning. On question 2, the teachers labeled b, c, and e focused their post-activity answers on the importance of conducting inquiry-based laboratory activities, which may help the students to discover how the world works and, at the same time, how scientific knowledge is produced. The teachers c and e also point out the organizational benefits of learning environments that promote students' involvement in group investigations and peer discussions. On the other hand, the teachers a and d, even admitting the benefits of a such explorative learning approach, show some concerns about the possibility to include this method in their teaching practice.

Before this OI experience, the teachers' first thought in front of an unexpected mismatch between a finding and the theory was that they actually made some mistake on collecting the data (Appendix C, question 3). In this respect, post-activity answers pointed out a change in their view of unexpected results, which now they even welcome in order to stimulate the students to cooperate, and inquiry the Nature to find a reasonable solution to the problem. All interviewed teachers mentioned in their post-activity answers the possible benefits of letting the students to face mismatches between theoretical predictions and experimental findings, mainly because of the opportunity to introduce the learners to a more realistic view about the work of scientists on building new pieces of scientific knowledge. However, the same teachers showed some perplexity about this as an established teaching strategy, because of the great cognitive effort requested to the students to overcome the observed mismatch, possible generation of uncomfortable feelings and reduction of teacher's credibility. They became aware of the great effort that is necessary in order to plan and prepare an inquiry-based teaching sequence to be submitted to the students. However, they also got that this preparatory phase can help the teacher to understand how effective is the process of conceptual knowledge construction, by providing a more realistic and attractive vision of scientific practices.

In their pre-activity answers to question 4, interviewed teachers provided a view of physics laws in terms of rules describing natural phenomena, perfect mathematical expressions that cannot be wrong, because already experimentally verified many times. On the other hand, post-activity answers pointed out that this OI experience was also useful to our teachers in order to clarify the role of a physics law within the context of a learning environment, where theory and experiments are both on the same level. In this respect, teachers' (b, c and d) answers to the post-activity interview highlighted this change in terms of a clear understanding that a physics law cannot be considered a rigid piece of knowledge, but rather an instrument to be used jointly with experiments to draw conclusions and extend our understanding of the world. It is also noteworthy the answer provided by teacher e, who explicitly mentioned the importance of introducing the students to the limits of validity of a physics law.

On answering question 5, concerning the importance of taking into account external factors within the plan for an experiment, the teachers stated that in their past laboratory practices they always considered a physics experiment as a stand-alone event, without any connection with the world outside the workbench. In particular, teachers b, c and e associated the effects of external factors to the presence of errors in their measurements or "mistakes" during instruments' calibration, without mentioning external physical interactions that could affect their experiment. Post-activity answers indicate that this OI experience helped the teachers to understand the fundamental role of the surrounding environment in some experiments and the need to take the boundary conditions always under control.

A practice usually named by teachers for assessing the students' understanding of the concepts after a laboratory session consists in inviting them to write a report summarizing the laboratory activities, and explaining the aims, the methods, the measurements and the conclusions for that specific experiment (read, for example, the answer 1.1c+d in Appendix C). This IO experience helped the teachers to realize that this latter form of evaluation is probably more oriented towards the development of memory skills than focused on students' reasoning capabilities (answer 1.2d). Better ways proposed by the teachers for assessing what students gained from a laboratory session now explicitly include an evaluation of the development of students' reasoning capabilities, which can be strengthen by performing inquiry-driven activities, such as "planning investigations, making hypotheses, interpreting and discussing data“ (citing answer 1.2d). Nevertheless, the promotion of students' peer-to-peer debating practice – searching all together for information in books or on the internet, presenting the results to colleagues and trying to convince them of their validity – is still considered an effective teaching strategy (Appendix C, answers to questions 6 and 7).

In summary, the OI-based teaching/learning approach followed during the workshop provided the teachers with the opportunity to experience a research-like activity and rediscover (or, maybe, discover) the original spirit of the scientists' work, which has nothing to do with fruitless demonstrations but it is focused on the process of knowledge construction by carrying out inquiry-driven experiments and discussing about unexpected results.

Our teachers personally experienced the basic methods on how to conduct a scientific investigation, starting from an initial phase of planning activities and continuing by designing and performing measurements, gathering and analyzing data, formulating hypotheses and models, and drawing conclusions. The analysis of teachers' responses to the interview makes evident that this OI experience stimulated the teachers to develop the awareness of the importance of (a) the documentation, not only at the beginning but extended throughout the entire process, (b) the need of maintaining constant conditions during an experiment, (c) observation reliability, (d) repetitions of measurements, maybe using statistics, (e) taking the boundary conditions under control, and (f) interacting and sharing the results of their work with the other people involved in the same research. The way this process happened is explained by considering the teachers' reasoning bringing about the evolution of their learning path through the stages of the OI teaching/learning workshop. For example, the teachers gained the awareness of the educational potentialities that could derive from an observed mismatch between data and theory. This result, explicitly reported by teachers' answers, is directly related to the teachers' behaviour observed during the OI workshop, where only after having repeated the measurements a couple of times and having found results not fitting with their initial working hypothesis, the teachers were finally convinced about the robustness of their measurements and started to pose questions, searching for plausible physical explanations of the observed mismatch. The subsequent phase of thinking-aloud together was also very useful. In fact, the result from their collective reasoning activity was the formulation of new hypotheses, such that of taking into account the effect of a changing ambient temperature, and the design of further experiments to check their validity. This effort provided the teachers with a strong evidence of the learning potential of an unexpected event, with respect to the usual teaching practice of completely guiding the students through a step-by-step procedure, where everything is known in advance.

The way our teachers approached this OI experience, in particular for what concerns their search for theories explaining the observed findings, such as their beliefs on the absolute value of the Stefan's law, showed a well defined conception of the physics laws as perfect entities expressing the rules governing the natural phenomena. However, the learning path they carried out during this OI workshop on thermal radiation showed a continuous switching between experiments, results' analysis and theory-driven explanations. This evolution of their habits of mind, with respect to the usual "Let's verify the physics law" approach, was naturally undertaken throughout a questioning and reasoning activity that are typical of inquiry-based pedagogies. The teacher's mention of the importance of introducing the students to the limits of validity of a physics law has also to be considered as a consequence of what that teacher directly experienced during the OI workshop, where the Stefan law was initially considered in the limit of validity of a constant ambient temperature. At this regard, the need the teachers encountered during the OI workshop to reconsider the Stefan law in its general form, by including the effect of a changing ambient temperature, played a significant role on their way of considering possible external effects caused by the environment.

Chapter 5

General discussion and conclusions

5.1 Guided-inquiry based learning at secondary school: Impact of inquiry-based teaching strategies on students' motivation and social aspects

In inquiry based instruction, the amount of information and support provided by the teachers may affect the learning efficacy on specific conceptual and/or epistemological targets. Usually, in GI the teacher provides the students with the research questions, and the students design the procedures to find reasonable answers and/or test the resulting explanations. Moreover, independently of the level of teacher guidance, the way the inquiry process itself is driven within the class has direct consequences upon the epistemological ideas that students might bring to bear on their work and on how the learning activity may change their perspective on scientific knowledge (Sandoval, 2005; Oliveira et al., 2012).

Recent studies suggest that a physics instruction based on GI, without providing an explicit attention to NOS aspects, seems to be more effective on repairing students' misconceptions (Nottis et al., 2010), with respect to produce useful epistemological perceptions of science (Bell et al., 2003).

Many researchers have become increasingly interested in the interplay between science conceptual learning and other cognitive factors, such as personal learning frameworks (Hogan, 1999), learning beliefs, and science epistemologies (Hammer & Elby, 2002). It has been shown that students' epistemological beliefs about science play a significant role on their ability to solve physics problems (Bing & Redish, 2009, Kuo et al., 2013).

From an epistemological perspective: *Inquiry is the process of doing science.* There are two main reasons why an understanding of scientific epistemology needs to be included as a fundamental aspect within inquiry-based science education:

i. The understanding of epistemological frames, characterizing the inquiry approach, will help the students to gain the awareness of their cognitive processes, causing an improvement of their learning performances;

ii. The development of sophisticated epistemologies of science would provide powerful tools for thinking to citizens in their everyday lives.

In order to design an effective inquiry-based instruction, it is not sufficient to know what students know about a topic. One must consider the opportunity to produce a fruitful change on students' epistemologies of science, which are not globally robust beliefs that drives students' learning and problem-solving, but rather context-dependent locally-coherent views whose stability depends both on external inputs and on students' internal conceptions and emotional states (Gupta & Elby, 2011). At this regard, a very recent study support the efficacy of an *implicit* method of NOS instruction for students enrolled in classes using the *Physics by Inquiry* curriculum (Lindsey et al., 2012).

In this thesis, the author has reported and described the results obtained from questionnaire administrations to a sample of lower and upper secondary school students who experienced a GI-based learning path explicitly developed within the context of ESTABLISH, a FP7 European Project aimed at promoting inquiry-based strategies for teaching science in European secondary schools.

The first research question addressed in this context has been focused on the basic ideas that secondary students have on school science and about the social impact of scientific knowledge on everyday life. A noteworthy result is that students seem to have a view of the science they study at school completely different from their conception of the scientific work made by scientists. Along their lives, the students have developed the common people view of school science as a subject characterized by a list of theories and laws to memorize and famous experiments explaining the behaviour of natural phenomena. In this respect, they believe that science arguments are interesting and stimulate curiosity. They also agree that everybody should learn science at school because scientific knowledge explains how the world works and could be useful for everyday life. However, despite these positive opinions about science, the students seem to do not consider the job of scientist as a plausible career opportunity, preferring, with some degree of uncertainty, a job in technology. This result can be ascribed to the fact that students consider the work of scientists too far from the real world, maybe not within everyone's reach, while nowadays they are more attracted by computer-based technology.

With respect to their younger colleagues, students attending upper secondary schools showed a little greater awareness of the difficulty to learn science concepts and a little less interest for scientific knowledge. Despite this, they believe that everybody should learn science at school. Even upper secondary students do not considered scientific careers as a good opportunities for their future employment. Some uncertainty is also expressed for what concerns the impact of science in our way of living and health care.

Post-instruction global result is that the GI-based learning path experienced by our students had a relatively modest impact on their perceptions. Only some minor changes have been recognized, suggesting a slightly increase in the awareness of the difficulty of learning science and a little more consideration about the opportunity to get a job in science and technology. The students were conscious of the importance of learning science even before the beginning of their ESTABLISH experience and on the potential role science and technology may play in our everyday life. But probably they were missing the connection to some practical examples that could help to consider science so important. In this respect, by engaging the students to personally explore the methods of scientific inquiry applied to the real context of building a low energy house, this learning experience provided the students with a concrete example of how important is the knowledge of science in their everyday life. This experience should have helped the students to realize that no difference exists between science at school and the real scientific work, and that scientists are no more than exceptionally curious people, strongly motivated to know and understand how the world works. The lack of interest showed by our students for scientific jobs could be ascribed to a misunderstanding of this point or even to other personal motivations.

The second research question addressed in the context of ESTABLISH has been oriented toward the comprehension of the extent a GI-based teaching approach can be suitable for achieving a change in students' perceptions of the nature of scientific knowledge. In order to answer this question, a questionnaire about those aspects of NOS which are the most commonly observed in students' discussions about science has been submitted to the students.

Our secondary students answered to the pre-instruction administration of the questionnaire as expected in learners who have never been involved in the practice of science. The main cognitive obstacles to the learning process have been recognized through students' answers highlighting: (i) the fact of considering the textbook (and the formulas therein) the main source of knowledge, independently from personal experiences, (ii) a theory as an unchangeable piece of knowledge, (iii) the importance of remembering facts. The relevance of considering the textbook the only source for learning science with respect to personal experiences has been found more relevant in lower secondary students, probably because older students have more experiences with real world phenomena or more used to study through web resources in which simulated physics experiments may provide the awareness of importance of experiential practices in addition to the textbook. Before being engaged in GI-based experiences, high percentages of both lower and upper secondary school students answered that remembering facts is very important to understand science. This finding being symptomatic of an excessively transmissive teaching approach from their teachers. At this regard, students' answers also highlighted the fundamental role they assigned to mathematical formulas in science learning. This fact could be ascribed to a misleading approach to problem solving, in which more attention is paid to the procedure with respect to the reasoning underlying the resolution process.

The experiences of the GI learning path produced an overall improvement of students' conceptions about the investigated NOS aspects. However, this result is barely noticeable in lower students' answers, while a little more evident in upper secondary students' outcomes. Globally, our results suggest that secondary school students, engaged in GI-based experiences and without any specific instruction on NOS, experienced modest changes in their views on how scientific knowledge is produced and characterized, confirming what expressed in recent literature at this regard.

The third research question addressed in the context of ESTABLISH experimentation has been focused on the efficacy of a GI-based teaching approach to motivate the students to learn science. Motivation, affects and beliefs about knowledge play a critical role in the learning process of scientific disciplines (e.g., Fennema, 1989; Schoenfeld, 1992) and the achievement of high order performances and skills is related to the motivational and affective boost of the learners. The two ESTABLISH questionnaires partially addressed this topic by collecting students' opinions about their interest in science. A majority of secondary students asserted that school science is interesting and everybody should learn science at school. In addition to the ESTABLISH survey, the students were asked to express their agreement about five motivational aspects selected among those proposed by Glynn and Koballa (2006): (i) *Intrinsically Motivated Science Learning* (I enjoy learning science; I like science that challenges me; understanding science gives me a sense of accomplishment.); (ii) *Extrinsically Motivated Science Learning* (I like to do better than the other students on science tests.); (iii) *Personal Relevance of Learning Science* (I think about how I will use the science I learn; the science I learn has practical value for me.); (iv) *Self-Determination to Learn Science* (If I am having trouble learning science, I try to figure out why.); (v) *Self-Efficacy for Learning Science* (I am confident I will do well on the science tests.). The students rated these aspects both prior to and after the GI-based experiences.

The answers provided by the students clearly demonstrated that they received a positive impression from the participation to the ESTABLISH project. Even considering that a majority of them, in particular lower secondary students, asserted to enjoy learning science even before the beginning of this experience, the higher feedbacks recorded after the GI-based learning path indicate a great appreciation of the project activities. Post-instruction data also showed an increase of the percentages related to the item concerning science as a challenge, confirming the benefits of this inquiry approach to intrinsically motivate the students to learn science, and those concerning the sense of accomplishment they feel when they understand science. The experience of inquiry learning, by stimulating collaborative work, reduced the feeling of competition among students on science tests, even considering that the students' answers highlighted a greater personal involvement on science tests.

In summary, the students globally appreciated their inquiry-based learning experience and an evidence of an increased motivation to learn science has been found in their answers. However, this result alone seems to be not enough to effectively impact on their vision of science and on their conceptions about the way scientific work is produced with respect to the science they study at school. As reported in recent literature (Sadeh & Zion, 2009), this finding could be ascribed to the medium-high level of guidance provided by the teachers through all the stages of the inquiry process, limiting the development of a deeper understanding of the essential meaning of conducting a scientific research.

5.2 Open-Inquiry experiences at University: Conceptual knowledge and epistemological issues on problem solving in engineering undergraduates

In OI-based instruction, the teacher takes the delicate role of defining the context for inquiry, stimulating the students to derive their own questions, design and carry out autonomous investigations, construct coherent explanations, share their findings. This teaching strategy should be helpful to develop higher skills of scientific thinking, but, at the same time, it requires the students to face great reasoning efforts.

In the last decade, several studies have addressed the question of the efficacy of an OI methodology on teaching science concepts and/or developing NOS views, in comparison with traditional instruction or GI-based teaching approaches. Berg et al. (2003) report a better conceptual understanding in students carrying out the same experimental activity by following an OI-based laboratory with respect to those following an expository-structured learning path. An in-depth comparison between GI and OI learning approaches was presented by Sadeh & Zion (2009), who compared the mean scores achieved by two groups of 12th grade students. In their study, the OI group outperformed the GI one only in aspects concerning the perspectives of critical and reflective thinking about the process.

Students involved in OI learning experiences have the purest opportunity to act like scientists and, in this way, they would gain a deeper view of the NOS and the awareness of the process of scientific inquiry (Capps & Crawford, 2013). Unfortunately, this latter approach, requiring the greatest cognitive demand from students in terms of scientific reasoning, may induce feelings of inadequacy or frustration, due, for example, to achieving of undesirable results, and could not bring about an effective understanding of the concepts (Millar, 2012).

The guiding idea of the scientific research described in this thesis has been that OI-based teaching strategies, promoting an involvement in activities similar to those carried out by scientists, should provide the students with the opportunity to deepen their understanding on how scientific knowledge is produced in real research contexts. In addition, the engagement of the students within highly motivated inquiry-based learning environments should avoid the development of negative affective components.

By following these lines, an OI-based learning environment has been designed to be experienced by a sample of mechanical engineering students having already received the traditional physics instruction in their university curriculum. The students were selected to be engaged in a pilot project, specifically aimed to investigate the efficacy of an OI-based approach to support the development of high levels problem-solving skills related to both design and inquiry procedures, as well as promoting a more meaningful conceptual understanding of the physics underlying the world of thermal phenomena. Students spent a total amount of about forty hours to plan and realize a complete scientific research, concerning the experimentation of ideas, the design and practical realizations of smart devices, in the context of a hypothetical project about the construction of a thermodynamically efficient space base on Mars. A questionnaire, specifically developed and validated to investigate the presence of epistemological constraints and residual conceptual difficulties affecting the complete understanding of common life phenomena in thermal science, has been administered to the students both prior to and after the OI experience.

Students' outcomes to the questionnaire have been deeply analyzed in order to answer the first research question addressed in this study. Three epistemological profiles for problem solving were identified and associated to the following student answering strategies: (i) The practical or everyday strategy, characteristic of those students who provide explanations basically grounded on everyday commonsense; (ii) the descriptive strategy, associated to college level students who study physics laws and theories in a purely mnemonic formulation, bringing to a factual knowledge of unrelated concepts; (iii) the explicative strategy, which refers to students who achieved a high level of an effective knowledge, which makes them able to search and find explicative models for the resolution of common life scientific problems.

The statistical analysis of the similarity relationships between students and the three ideal student profiles allowed us to clarify how students modified their epistemological stances with respect to facing thermal phenomena and solving related problems, as a result of the attended OI-based learning experiences (research question 2). Data reported in Figures 4.2 and 4.3 show that the distribution of the student similarity indexes with respect to the three ideal profiles have been significantly affected by the OI type instruction. In fact, pre-instruction results show the presence of a main cluster of similarity, with respect to the de-type ideal profile and of a less populated one, mainly related to similarity with the ex-type profile. Figure 4.2b clearly shows the presence of a post-instruction single ex-type cluster of similarity, with components often pointing out also the use of descriptive-type strategies.

A general significant reduction in the number of post-instruction answers related to the pe-type approach has been found. This essentially means that less students now consider their personal commonsense interpretations as valid explanations of the observed phenomena. However, the most significant result regards those students originally adopting a prevalent de-type approach, which is basically characterized by attempts to find a mathematical solution to the problem, without considering conceptually meaningful physical explanations. In fact, while at the beginning of the project the students showed the higher levels of similarity with the de-type profile, at the end of activities the majority of them adopted ex-type reasoning strategies.

With respect to the third research question, we have observed that a significant fraction of students, already instructed by attending traditional courses on thermal science, shows residual conceptual difficulties on facing and solving the proposed situations, as also highlighted by other researchers (Prince et al., 2012). We have found high percentages of students who provided problematic answers to questions requiring the effective application of the concept of specific heat or still considering heat as a storable quantity, instead of the energy exchanged because of a temperature difference, showing significant difficulties in identifying the relevant physical quantity involved in a dynamic process characterized by two or more variables, confirming the results reported in Jasien & Oberem (2002) and Prince et al. (2012). Other difficulties, not exclusively related to misconceptions, were experienced by our undergraduates when answering to questions about heat transfer by multiple transport mechanisms. On writing their solution, students usually take into account only one transport mechanism, probably the one they believe to be dominant, and do not even consider the possibility of a combined action with the others. The problem of "forgetting to mention" a mechanism was observed in our student sample for convection or thermal radiation, but not in the case of thermal conduction. The latter is the most known mechanism to the students, though the other two are equally experienced in their everyday lives, but probably without being completely aware. Thermal conduction needs the presence of a medium to transport the energy and people seeing the medium can easily imaging something (thermal energy) that travels across it. Convection needs a medium too, but learners have more difficulties to figure out the motion of the particles when the fluid is not visible, such as the air. In this view, thermal radiation, being able to travel even in the vacuum, is the transport mechanism that the students most easily forget to take into account, even if they are, of course, aware of the heating mechanism by solar radiation. The last difficulty we have noticed in our students specifically regards their approach to answer the pre-instruction questionnaire: when facing a problem, some students immediately started by opening the 'handbook of the engineer', trying to catch the right formula to be used to answer the questions. This behavior could be ascribed to their past learning experiences, which were probably too much concentrated to memorize formulas and solve standard problems by applying defined procedures, instead of deepening their view of science as a global challenging research for coherent explanations.

In post-instruction data we observed a clear reduction of the percentage of students showing conceptual difficulties and a significant increase of answers related to explicative-type reasoning. Recent studies have shown the pedagogical effectiveness of incorporating guided inquiry-based activities, concerning the topic of heat transfer, on concept understanding (Nottis et al., 2010). Despite research findings reported in literature evidence that students attending OI-based instruction achieve higher levels of critical thinking skills and understanding the nature of science (Yen & Huang, 2001; Zion et al., 2004; Sadeh & Zion, 2009), but not necessarily repair their misconceptions (Quintana et al., 2005), our results indicate that the students have globally improved their understanding of the basic concepts of thermal physics.

The way students answered the questionnaire before and after instruction also gave us insights about a change in their way to approach the proposed situations. In fact, before instruction they considered the questionnaire as a sort of evaluation test, searching for possible formulas in their engineering manuals and answering the questions with short, mathematically oriented solutions. After the OI experience, they approached the questionnaire in a more competent way, by trying to explain their answers, inquiring about the described phenomenon and reasoning on the dominant energy transport mechanism and the most relevant physical quantities involved in the processes. This finding is confirmed by the observed reduction in the number of post-instruction implications involving pe-type and de-type responses and by the increase in the number of implications regarding the ex-type typology. The global improvement in the students' problem-solving strategies, quantitatively established by the percentage increase of implications between post-instruction ex-type answers to different questions, is a clear indicator of the efficacy of OI-based learning activities to activate more efficient problem solving skills. However, since our study does not compare open and guided inquiry-based teaching approaches, we cannot exclude that a guided inquiry-based learning environment would produce positive outcomes as well. Nevertheless, our results put in evidence that OI experiences contribute positively to increase student abilities in problem solving, by providing the activation of appropriate epistemological resources.

Finally, although some studies (Trautmann et al., 2004; Quintana et al., 2005) showed that OI-based teaching/learning approaches, requiring the greatest cognitive demand from students in terms of scientific reasoning, may induce feelings of inadequacy or frustration, preliminary analysis of our video-recorded data do not show any evidence of this. The choice made by the educators to drive the students' inquiry within the context of a space science challenge strongly motivated the students. They were, of course, conscious that their research work was not part of a real space project, but they participated to the activities with equally high emotional involvement, being convinced of the importance of actively participate to a real research experience. After the conclusion of this experience many students spontaneously emailed the educators their positive feedback, highlighting the benefits of this OI learning environment in terms of developing practical and reasoning skills about learned concepts. Moreover, even if not required, each student group prepared an oral contribution describing the OI experience and enthusiastically presented the results of their experimental activities in front of the Faculty Council for Mechanical Engineering. In conclusion, it appears that our students very much appreciated this "new" teaching approach, confirming that a highly motivating OI-based learning environment may minimize the appearance of negative psychological effects.

5.3 The teachers' perspectives on inquiry-based pedagogies in their classroom practices

Despite an intensive call for reform, the consensus from the science education community is that there has not been a substantive increase in inquiry-based practice (Windschitl, 2001; Moss, 2003; Wallace & Kang, 2004). The various calls from the science education community for more research focused on professional development for pedagogical content knowledge of inquiry is based on a recognition that the body of knowledge about how to successfully conduct such development is very limited (Keys & Bryan, 2001). A likely reason for this omission in the literature is that a pedagogical content knowledge of inquiry demands a high level of expertise (Crawford, 2007).

In this thesis, the perceptions of secondary school teachers about inquiry have been investigated within two contexts of inquiry experimentation: GI at secondary school and OI at university. The term “perception” was defined in this research as the teachers’ capacity to recognize and describe the pedagogical features of their inquiry-based research experience.

5.3.1 Inquiry Content Knowledge from teachers’ GI-based teaching experiences

Anderson (2003) stated that implementation of inquiry learning is limited by beliefs held by many teachers such as, “knowledge as facts, teaching as telling, and learning as memorizing” and a view of factual knowledge as the most important student outcome, achievable through repeated exercises and practice (Cronin-Jones, 1991). Teachers using transmissive instructional methods are challenged to develop new content knowledge, pedagogical techniques, approaches to assessment, and classroom management (Marx et al., 1994). However, teachers cannot simply move to inquiry approaches of instruction directly from direct instruction. They need to learn many new concepts about students, learning, curriculum, pedagogy, and assessment (Wilson & Berne, 1999). The development of such expertise can be difficult to attain. Teachers must be able to combine several important kinds of knowledge in order to successfully implement classroom science instruction for concept learning (McDermott, 2006). These should include knowledge of both science content and scientific inquiry pedagogy. A theoretical knowledge of each one is not enough. Physics education researches have clearly shown that teachers aren’t able to make the transition from a purely transmitting didactics to an inquiry based one only through the illustration of new methods and strategies (Pinto, 2004). A teacher needs to understand how to integrate content knowledge and inquiry pedagogy to make effective instructional decisions for teaching a variety of specific topics in actual classroom situations. This is exactly what ESTABLISH has aimed to do with future teachers involved in IBSE.

The Italian group of secondary school teachers involved in the project asserted to have rarely implemented teaching strategies based on scientific inquiry in their classrooms before this experience. Their pre-activity answers to the ESTABLISH questionnaire highlighted how much grounded on a teacher-centred pedagogy was their usual teaching practice. The teachers admitted to always provide step-by-step instructions to their pupils during laboratory activities. Their students were left with few opportunities to formulate scientifically relevant questions and they were almost never involved in designing the procedure for carrying out of a scientific investigation. The teachers were used to perform experimental activities in front of the class, as a merely demonstration of the validity of a physics law.

Pre-activity results highlighted a wide range of uncertainty in teachers’ responses concerning the understanding of IBSE and some perplexity about the time needed to implement inquiry-based teaching strategies in classroom. The teachers’ responses provided before their enrolment in ESTABLISH have clearly outlined a poorly-involving learning environment, where the students understand only “sometimes” the importance of gathering data and rarely are able to draw their own conclusions from laboratory investigations. The teachers, however, appeared to be conscious that a teaching approach based on fruitless demonstrations is not the most appropriate one to engage the learners and that, probably because of this, the students seldom connect the results of an experiment to scientific knowledge.

The participation to the ESTABLISH project provided the teachers with the opportunity to spend time to train themselves on inquiry pedagogies, by contributing to the preparation of the inquiry-based teaching unit and personally experiencing the benefits of involving the students into the practice of scientific investigations.

At the conclusion of their ESTABLISH experience, the teachers answered the questionnaire by rating higher their understanding of IBSE, identifying the roles of teachers and students more clearly within the inquiry-based teaching/learning approach. All of them recognized that inquiry is fundamental to make students start thinking more like scientists, that is, to acquire "critical thinking" abilities. At the end of the GI-based experience, more teachers believed that the lack of time to cover the whole curriculum applying inquiry methods in classroom is no longer a problem, since they could use inquiry to teach only part of the content, or to develop exclusively a limited number of laboratory experiences. In fact, after ESTABLISH, the teachers became more aware of the opportunity to use scientific inquiry to strengthen the reasoning skills of their students, independently of the content. In this respect, they strongly disagreed with those statements asserting that inquiry methods are only suitable for very capable students.

Post-activity teachers' responses showed marked changes on their views of teaching practice, as shaped by their participation to the ESTABLISH project. For example, before this GI-based experience, the strategy the teachers adopted to face the unexpected results obtained by their students in some experimental activity was almost completely focused on providing the right answer to their pupils. At the end of the project, the teachers asserted to be convinced of the importance of letting the students to inquiry and find the right answer to a question or problem by themselves. The ESTABLISH experience had certainly a positive impact on the teachers' view about the different activities the students may fruitfully carry out in groups. Some teachers now are also more convinced to stimulate the students by asking them to answer higher order questions.

Uncertain answers were recorded for what concerns the sufficient level of knowledge of science needed to develop the ability to implement an inquiry lesson effectively. Mark Windschitl (2003) highlighted what kinds of teacher knowledge and skills are required to design and guide students through different forms of laboratory activity. In this respect, he defined six different activity structures commonly used in classrooms that fall under the general category of laboratory work: Demonstrations, building skills, discovery learning, problem solving, school science inquiry, authentic forms of inquiry. Windschitl (2003) suggested a teacher training path developing disciplinary knowledge of inquiry, in terms of understanding the purposes of science inquiry, knowledge of domain-specific methods of investigation, understanding the nature of relationships between scientific models and data.

In this view, the participation to the ESTABLISH project had a very positive impact on our teachers. They have firstly strengthened their theoretical background of inquiry-based teaching methodologies and the subsequent experimentation carried out in their schools has been fundamental to understand how to put scientific inquiry into classroom practice. The teachers had the opportunity to explore the efficacy of an inquiry-based approach to involve the students to actively participate to the learning process and to introduce the student to the practical applications of science and technology in everyday life. Lastly, the teachers have definitely understood that their concerns about the time needed to implement inquiry in classroom and the additional knowledge required in technological innovations were not motivated, since both aspects can be treated within specific practical training paths.

Anderson (2003) and others asserted that most teachers are confused about the meaning of inquiry, and this confusion is among the reasons that teachers give for not implementing inquiry in their classrooms. Teachers may have these uninformed views about scientific inquiry as a result of the traditional portrayal of recipe-like experiments in science textbooks, as textbooks often play a vital role in understanding the process of science (Abd-El-Khalick, et al., 2008). It may therefore be reasonable to argue that science textbooks should be revised in line with the contemporary conception that there is no single scientific method to be used in developing scientific knowledge (Abd-El-Khalick & Lederman, 2000; Abd-El-Khalick, et al., 2008).

During their undergraduate preparation, pre-service teachers usually take a number of science content courses and a broad science teaching methods course. They are regularly assessed on their science content knowledge, but there is a critical need to complement this by also assessing pedagogical content knowledge of inquiry science teaching. During their training, characteristics of inquiry-based practices must be explicitly addressed from a epistemological point of view, as well as problem based activities that are not too much focused on specific disciplinary knowledge. In this way, teachers can activate the reasoning resources necessary for a profitable development of their pedagogical knowledge of scientific inquiry. Finally, teachers need to gain a more epistemologically congruent representation of how contemporary science is done by developing activities across different domains of inquiry and many types of investigations.

5.3.2 Teachers perceptions of OI-based teaching/learning methodologies

By following an OI-based teaching approach, a group of selected teachers was engaged in a learning path of self-directed research-like experiences, aimed at investigating the process of heat exchange by thermal radiation. The teachers were stimulated to ask questions, plan scientific investigations and design experiments, which were discussed all together and adapted to the equipments at their disposal in the laboratory. The teachers worked in group and collected, processed and analyzed the data, regarding the cooling process of a previously heated resistor inside an evacuated container.

Once the teachers collected the data, they found useful to stop their measurements for a while and discuss about what is actually known and published on literature on the specific problem under investigation. The teachers discussed the result of the comparison in terms of agreement or not between theory and experimental findings, by questioning about the observed disagreement and on what could have affected the data during the experiments. They compared their experimental outcomes with what expected from known theories, analysing also the findings already published in the literature from similar experiments. The teachers questioned about the results of the comparison: “Do our experimental data meet the theory?”. When the answer was “no”, as common in physics, the teachers were forced to check their experiment and think about what could have played a role in the observed mismatch. They considered new hypotheses and took into account new physical effects previously neglected. They soon turned back to the theory and conducted a new comparison. Being the agreement between theory and collected data still not completely satisfying, the teachers conjectured that maybe the values of some parameters they adopted, such as the heat capacity and/or emissivity, were not perfectly correct in the numerical solution of the Stefan’s law. Therefore, they performed further investigations on how the accordance between data and theory could have been improved by changing these parameters. The teachers continued their scientific investigation by observing and measuring other physical quantities that they believed could have had a significant role affecting the experimental results, such as the ambient temperature in the laboratory and the temperature of the vacuum tube containing the resistor. The teachers experienced a real scientific research activity, which sometimes can bring up to unexpected results, such as in the case of the effect caused by the change of the temperature of the surrounding environment into the energy transferred from/to a body by thermal radiation. A modified theory was suitably developed to take into account the new observations, and compared with the previously collected data. A final comparison between theory and experimental findings stimulated the teachers to drawn their own conclusions. Diagnosing problems, critiquing experiments, researching alternatives, searching information, constructing models and planning alternative investigations are the basic processes of an inquiry-based approach that teachers found relevant for the educational reconstruction of the physics content to be taught.

Even considering the limitations of a case study, our findings showed a globally positive feedback from the involved teachers, who considered this OI-based learning experience an effective way of scientifically investigating the physics of thermal emission by radiation. The analysis of the teachers’ answers to the interviews allowed us to highlight several changes on the teachers’ way of thinking about peculiar aspects of scientific practices, which were explicitly addressed within our OI workshop. The teachers appeared to gain the awareness of the many-faceted potentialities of this teaching approach and some of them would consider the possibility to take into account some aspects of the inquiry-based instruction methodology, as a valid integration to the traditional physics teaching. They found particularly relevant for their professional development the possibility offered by such OI approach to effectively reconstruct specific physics content knowledge from a pedagogical point of view (Sperandeo-Mineo et al. 2006; fazio et al., 2008). However, the teachers reported some concerns regarding both the time required to implement inquiry-based activities in classrooms and the level of guidance they should provide to students' inquiry. Finally, by mean of the post-activity interview, teachers involved in this OI workshop were also stimulated to reflect on the OI-based learning path experienced and implicitly guided towards the development of a pedagogical knowledge of the inquiry approach.

5.4 Final remarks and future opportunities

The development of scientific epistemology is an explicit goal of recent educational reforms, mainly driven by the conception that students' ideas about NOS influence their efforts to conduct (and learn) science. Of course, students need to understand disciplinary concepts and inquiry-based instruction is intended to help students' learning. Disciplinary scaffolds grounded within epistemic structures might guide students' inquiry and help them to see how to use disciplinary concepts to explain the observed natural phenomena. The use of integrated conceptual and epistemic guidance favors the activation of cognitive resources useful to articulate explanations.

In this thesis, results from questionnaire outcomes administered to secondary school students within the ESTABLISH project have shown great motivational responses but modest benefits from a GI-based instruction in terms of a deeper understanding about NOS aspects implicitly addressed. This result could be ascribed to a lack of reasoning efforts in students, who are guided by the teachers step-by-step across the inquiry-based learning phases and cannot be able to acquire a comprehensive view of the scientific enterprise. The students should be involved within highly motivating environments which may stimulate them to ask scientifically relevant questions, discuss and share their ideas and reinforce their critical attitudes and scientific thinking. This does not necessarily mean that secondary students must be instructed exclusively within an OI learning environment, where they would be left to follow their own questioning path, because probably still young to highly perform, but an integrated system of instruction should work fine.

At university, an effective teaching of physics at engineering should provide the students with an adequate background of discipline specific information and strengthen their creative thinking and design skills, with the general aim of promoting a vision of natural phenomena in terms of concepts and developing abilities of designing and putting in action brilliant problem-solving strategies.

Traditional methods of teaching thermal science at university, mainly based on the transmission of information and laws, bring about a not lasting and effective learning. The encouraging results presented in this thesis have been obtained by engaging and motivating a small sample of engineering undergraduates to perform independent OI-based research activities, which, however, were carried out over a short time interval. The application of OI-based strategies within learning experiences more extended in time could bring about to even better outcomes. However, even considering all the limitations of a case study, these findings provide positive indications towards the inclusion of design-based research-like activities, within an OI-based learning environment, in the standard curricula of engineering education, as a valid integration to traditional teaching. In this way, it could be possible to achieve a more useful and effective meaningful knowledge on difficult physics concepts, promoting the strengthening of the reasoning skills of future engineers and their vision of the nature of science.

Forthcoming results from the video analysis and students' interviews collected during this project will contribute to a better understanding of the dynamics involving the acquisition of metacognitive and autonomy skills, taking place during an OI-based instruction, and will be useful to improve the design of future learning environments for science and engineering students.

At last but not least, this study suggests some implications for promoting teacher education in the context of IBSE. Inquiry in science involves a range of cognitive, social, and physical practices and all inquiry-based approaches to science teaching suggest that students should "themselves engage in the practices and not merely learn about them secondhand. Students cannot comprehend scientific practices, nor fully appreciate the nature of scientific knowledge itself, without directly experiencing those practices for themselves" (NRC, 2012, p. 30). This can be also considered true for those teachers that in their curriculum have never been involved in a laboratory experience aimed at solving problems through an inquiry-based approach. The engagement of teachers who directly experiment the same learning environments they are supposed to use in their classrooms has shown its efficacy for teacher development. A single experience is probably not enough to allow teachers to gain familiarity with all the scientific practices, but it can give them insights about the role of experiments, inquiry procedures for a deeper analysis of data, evaluation of unexpected results, comparison with known theories or development of explicative models. Further experimentations of OI-based teaching/learning methodologies would provide a deeper understanding of the resulting formative processes, developing appropriate scaffolding procedures for the support of inquiry-based curricular implementations within the future university programs of physics teachers' education.

APPENDIX A: THE QUESTIONNAIRE

1) Two equal bricks are exposed to the sunlight for 15 minutes; one is placed vertically and the other one is placed horizontally with respect to the ground. What do we observe at the end?
   a) The temperature of the vertical brick is greater than that of the horizontal one.
   b) The temperature of the vertical brick is lower than that of the horizontal one.
   c) The two bricks are heated up the same temperature.
   d) I don’t know.

   Motivate your answer:

2) Two equal metal plates, the first one white-painted and the second one black-painted, are exposed to the sunlight in the same way and for the same time interval.
   Which of the two plates reaches the highest temperature?
   a) White.
   b) Black.
   c) They reach the same temperature.
   d) I don’ know.

   Motivate your answer:

3) Two equal aluminium cylinders, the first one white-painted and the second unpainted, are heated up to reach the same temperature and then left to cool. What do we observe?
   a) The white-painted cylinder cools first.
   b) The unpainted cylinder cools first.
   c) The two cylinders cool by maintaining the same temperatures.
   d) I don’t know.

   Motivate your answer:

4) Two equal plastic bottles, the first one filled with water and the second with sand, having almost the same weight, are exposed to the sunlight in the same way and for the same time interval (15 minutes); which of the two bottles reaches the highest temperature?
   a) The one filled with water.
   b) The one filled with sand.
   c) They reach the same temperature.
   d) I don’ know.

   Motivate your answer:

5) After having heated the two bottles of question #4 up to the same temperature, we bring them out from the direct exposure of sunlight and observe their cooling. Which of the two bottles is cooling faster?
   a) The one filled with water.
   b) The one filled with sand.
   c) They cool maintaining the same temperature.
   d) I don’ know.

   Motivate your answer:

6) Two ice cubes are extracted from the freezer and placed on top of two aluminium plates at room temperature, having the same surface but different thickness. It is observed that:
   a) The ice melts more quickly if placed on top of the thicker plate.
   b) The ice melts more quickly if placed on top of the thinner plate.
   c) The ice melts in the same way on top of the two plates.
   d) I don’ know.

Motivate your answer:

7) Two ice cubes are extracted from the freezer and placed on top of two aluminium plates at room temperature, having the same surface but different thickness. At the end of the melting phase we measure the average surface temperature of the two plates and we find that:
   a) The temperature of the thicker plate is lower than the that of thinner one.
   b) The temperature of the thicker plate is higher than the that of thinner one.
   c) The temperature of the two plates is the same.
   d) I don' know.

   Motivate your answer:

8) A glass beaker and a plastic cup are left empty inside a freezer for a whole night. The following day, the two objects are extracted from the freezer and the temperature of the glass beaker is immediately measured. It is:
   a) Higher than that of the plastic cup.
   b) Equal to that of the plastic cup.
   c) Lower than that of the plastic cup.

   Motivate your answer:

9) If you hold one end of a metal nail against a piece of ice, the end in your hand soon becomes cold. Does cold flow from the ice to your hand?

   Explain:

10) If you drop a hot rock into a pail of water, the temperature of the rock and the water will change until both are equal. The rock will cool and the water will warm. Is this true if the rock is dropped into the Atlantic Ocean?

    Explain:

11) A cool object placed in front of a fan:
    a) Heats up more slowly.
    b) Heats up more quickly.
    c) Heats up the same.

    Explain:

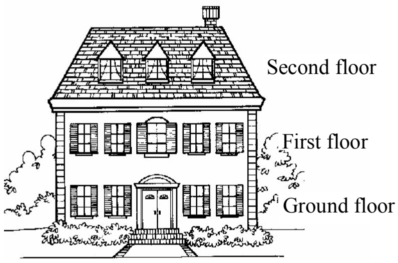
12) A warm object is arranged inside a glass jar bell from which the air is expelled by a vacuum pump. It:
    a) Cools anyway.
    b) Does not cool.
    c) I don't know.

    Motivate your answer:

13) In a house, two empty rooms having equal surface and identical exposure to the sunlight, have only one window, which is always left open during the day in the summer season. The only difference between the two rooms is the position height of the window: one is placed in the middle of the wall and the other is placed higher. Which of the two rooms is fresher?

    Motivate your answer:

14) In a three-story house there are three apartments, one for each floor, not equipped with heaters. The apartment at first floor is the warmest.



Try to guess the cause:

15) During a hot summer day the rooms upstairs are warmer than those downstairs. Why?

APPENDIX B: STUDENTS' ANSWERS TO THE QUESTIONNAIRE

Q1peA: "Ans_a) because of the greater surface of interaction with the surrounding environment".
Q1peB: "Ans_b) because of the greater surface exposed to the source of heat".
Q1peC: "Ans_b) because of the greater surface exposed to the Sun, therefore higher temperature".
Q1peD: "Ans_c) because it is likely that, after 15 minutes, the two bricks have reached the same temperature".
Q1peE: "Ans_d) because I have never experienced this phenomenon before".
Q1deA: "Ans_a) because of the greater surface of thermal exchange".
Q1deB: "Ans_b) because of the greater surface exposed to solar radiation, therefore it absorbs more energy".
Q1deC: "Ans_b) because the horizontal brick completely absorbs the solar power that hits on it".
Q1deD: "Ans_b) because of the Stefan law".
Q1deE: "Ans_b) because of the low temperature gradient (Fourier law) along the depth of the brick, therefore the horizontal brick will hold the heat for a longer time".
Q1exA: "Ans_b) because of the greater surface with greater orthogonal component to the incident solar radiation".
Q1exB: "Ans_b) because the increase of temperature is caused by the quantity of absorbed energy, which is greater when the surface is placed orthogonally with respect to the incident radiation".

Q2peA: "Ans_a) because the white colour contains all colours, including the black one and many more".
Q2peB: "Ans_b) because in the summer season objects painted by dark colours are hotter".
Q2peC: "Ans_b) because usually black objects absorb more heat".
Q2peD: "Ans_c) because, in my experience, colours do not affect the temperature of an object".
Q2peE: "Ans_d) because I have never experienced this phenomenon before".
Q2deA: "Ans_a) because the colour temperature corresponding to the white is the highest one".
Q2deB: "Ans_b) because the black colour is a combination of all bright bands and entirely absorbs radiations".
Q2deC: "Ans_b) because the refraction index is lower in the black plate with respect to the white one".
Q2deD: "Ans_b) because the black body is the perfect body absorbing light".
Q2deE: "Ans_b) because the black body is the perfect body absorbing thermal energy, therefore the black plate is heated more than the white one".
Q2deF: "Ans_b) because the black plate has a lower emissivity with respect to the white one".
Q2deG: "Ans_b) because the black body is the best emitter, $\varepsilon=1$".
Q2exA: "Ans_b) because the black colour increases the absorption factor".
Q2exB: "Ans_b) because the black colour means that all visible radiation is not reflected but absorbed".
Q2exC: "Ans_d) because it depends on the absorption coefficient of the paints".

Q3peA: "Ans_a) because the white colour is the brightest and let more energy to come out of the white cylinder".
Q3peB: "Ans_b) because in this case the energy is more free to leave the cylinder".
Q3peC: "Ans_c) because they are made by the same material and, in my experience, colours do not affect the temperature of an object".
Q3peD: "Ans_d) because I have never experienced this phenomenon before".
Q3deA: "Ans_a) because the perfect white body is the ideal emitter of light".
Q3deB: "Ans_b) because the paint has a lower conductivity with respect to the aluminium (values reported from a handbook)".
Q3deC: "Ans_b) because aluminium has a polished surface and therefore reflects better".
Q3deD: "Ans_b) because the white surface emits a lower quantity of heat by thermal radiation".
Q3deE: "Ans_b) because the white paint could function as a thermal insulator, permitting a slower transfer of heat".
Q3deF: "Ans_b) because the white paint lowers the cylinder conductivity".
Q3deG: "Ans_c) because convection is the prevalent cooling mechanism".
Q3deH: "Ans_c) because, neglecting insulation effects, the colour of the paint should not affect the cooling process".
Q3deI: "Ans_d) because it depends on the thermal conduction coefficient".

Q3exA: “Ans_a) because the paint has a greater emissivity”.
Q3exB: “Ans_a) because the polished aluminium cylinder is characterized by a low emissivity and the paint increases the emissivity”.
Q3exC: “Ans_a) because the two cylinders emit radiation in the infrared and the paint has a greater emissivity in that range of electromagnetic spectrum”.

Q4peA: “Ans_a) because I can see through the water and this means that solar radiation can penetrate inside the bottle filled with water and warm it more easily.
Q4peB: “Ans_b) because, during a summer day at the seaside, we feel the sand hotter than the sea water…it should depends on the specific heat”.
Q4peC: “Ans_c) because I can’t see any difference between the two bottles”.
Q4peD: “Ans_d) because I have never experienced this phenomenon before”.
Q4deA: “Ans_a) because the sand is a thermal insulator”.
Q4deB: “Ans_a) because the specific heat of the water is greater than that of the sand and the specific heat is the physical quantity which gives information on heat storage”.
Q4deC: “Ans_a) because the thermal conduction coefficient of the water is greater then that of the sand”.
Q4deD: “Ans_a) because water absorbs energy more quickly”.
Q4deE: “Ans_b) because of a lower thermal conductivity”.
Q4deF: “Ans_b) because of the higher specific heat of the sand”.
Q4deG: “Ans_b) because sand should have a greater thermal conductivity”.
Q4deH: “Ans_b) because the sand is opaque to solar radiation and therefore the surface heats up more quickly”.
Q4exA: “Ans_b) because the specific heat of the sand is lower than that of the water”.
Q4exB: “Ans_b) because the increase of the temperature is inversely proportional to the specific heat and that of the sand is lower than that of the water”.
Q4exC: “Ans_b) because we need less energy to heat sand with respect to what we need to warm the same amount of water (calculations by means of specific heat reported).

Q5peA: “Ans_a) because water is transparent and releases out energy more quickly”.
Q5peB: “Ans_b) because at the seaside during the night the sand cools faster than the sea water”.
Q5peC: “Ans_b) because the sand is a solid material and cannot storage a big amount of heat ”.
Q4peD: “Ans_c) because I can’t see any difference between the two bottles”.
Q4peE: “Ans_d) because I have never experienced this phenomenon before”.
Q5deA: “Ans_a) because convection facilitates heat dispersion”.
Q5deB: “Ans_a) because a lower thermal conductivity brings to a greater difference in temperature”.
Q5deC: “Ans_b) because of the thermal conductivity”.
Q5deD: “Ans_b) because the specific heat, which is the physical quantity related to the storage of heat, is greater in the bottle filled with water”.
Q5deE: “Ans_b) because sand emissivity is higher than that of the water”.
Q5exA: “Ans_b) because the specific heat of the sand is lower than that of the water and, therefore, a lower amount of energy is needed to cool it”.
Q5exB: “Ans_b) because, being the specific heat of the sand lower than that of the water and assuming the same quantity of heat subtracted, the sand will reach soon a lower temperature”.
Q5exC: “Ans_b) because, by assuming the same amount of energy subtracted, the temperature of the bottle filled with water will be higher than that one filled with sand because of its higher specific heat”.

Q6peA: “Ans_a) because heat absorbed by the ice cube is greater from the thicker plate”.
Q6peB: “Ans_b) because the thinner plate has a lower insulation effect to the heat transfer from the table”.
Q6peC: “Ans_c) because the temperature of the surrounding environment is the same”.
Q6peD: “Ans_c) because only the contact surface is important, not the thickness”.
Q6peE: “Ans_d) because I have never experienced this phenomenon before”.
Q6deA: “Ans_a) because aluminium is a good thermal conductor”.
Q6deB: “Ans_b) because the speed of heat transfer by conduction is inversely proportional to the thickness, therefore the thinner plate transfers more heat to the ice cube”.

Q6deC: “Ans_b) because the thermal power is inversely proportional to the thickness (formula)”.
Q6deD: “Ans_b) because of the Fourier law (equation)”.
Q6deE: “Ans_c) because of the Zero Law of Thermodynamics”.
Q6exA: “Ans_a) because the thicker plate, having a bigger mass, has much more particles with kinetic energy 1/2 mv^2=3/2KT, which is available to be transferred as heat to the ice cube”.
Q6exB: “Ans_a) because the thicker plate absorbs heat from the ice cube more faster because of its greater thermal capacity”.
Q6exC: “Ans_a) because the heat transfer from the plate depends on its thermal capacity, which is greater in the more massive one”.

Q7peA: “Ans_a) because a big object is more resistant to changes (in temperature) with respect to a smaller one”.
Q7peB: “Ans_b) because the thicker plate has a greater insulation effect to the heat transfer from the table”.
Q7peC: “Ans_c) because the temperature of the surrounding environment is the same”.
Q7peD: “Ans_c) because only the contact surface is important, not the thickness”.
Q7peE: “Ans_c) because, just after the ice melting, the two surfaces are both at zero centigrade degrees”.
Q7peF: “Ans_c) because the two ice cubes start from the same temperature”.
Q7peG: “Ans_d) because I have never experienced this phenomenon before”.
Q7deA: “Ans_a) because the thermal power of the thicker plate is lower”.
Q7deB: “Ans_b) because the thinner plate dissipates heat better and more quickly”.
Q7deC: “Ans_b) because of thermal conduction, the Fourier law (equation)”.
Q7deD: “Ans_b) because of the lower thermal capacity of the thinner plate”.
Q7deE: “Ans_b) because the body with lower volume is heated/cooled faster”.
Q7deF: “Ans_c) because of the Zero Law of Thermodynamics: both plates will reach the ambient temperature”.
Q7exA: “Ans_b) because the thicker plate has more thermal energy”.
Q7exB: “Ans_b) because the thicker plate, having a bigger mass, has much more particles with kinetic energy 1/2 mv^2=3/2KT to be cooled by the ice cube”.
Q7exC: “Ans_b) because, by using the heat definition (formula), we know that in order to change the temperature of a more massive object we need a greater amount of heat”.

Q8peA: “Ans_c) because I feel the glass beaker colder”.
Q8peB: “Ans_c) because, even at ambient temperature, glass is always colder than plastic”.
Q8deA: “Ans_a) because the glass is a less efficient thermal insulator”.
Q8deB: “Ans_b) because, after waiting for many hours, thermal conduction inside the freezer is the same”.
Q8deC: “Ans_c) because the glass density is higher than plastic one”.
Q8exA: “Ans_b) because the time is enough to reach the thermal equilibrium with the freezer”.
Q8exB: “Ans_b) because of the Zero law of Thermodynamics”.

Q9peA: “Yes, because it is the same phenomenon of an open window during the winter”.
Q9peB: “Yes, because the metal is a good thermal conductor, as in the case of a spoon in a cup of hot chocolate”.
Q9deA: “No, cold does not exist as a form of energy, heat is energy on transit”.
Q9deB: ”Yes, because of the greater thermal conductivity of the metal nail”.
Q9deC: “The metal has a high thermal conductivity and, for the Zero Law of Thermodynamics, the temperature goes from the hand to the ice”.
Q9exA: “No, because by following the second principle of thermodynamics, heat naturally flows towards decreasing temperatures”.
Q9exB: “No, heat flows from hot to cold bodies”.

Q10peA: “No, because the volume of the ocean is very big and, therefore, its temperature cannot change”.
Q10peB: “Yes, but the ocean remains at the same temperature because its dimensions are much more bigger”.

Q10deA: “Yes, but the sea remains at the same temperature because its mass is much more greater”.
Q10deB: “No, because the ocean can be considered a thermal reservoir”.
Q10deC: “The temperature of the ocean changes in a very little volume around the hot rock only. Then the system will reach back its initial temperature”.
Q10deD: “Sure, because the temperature is an intensive quantity ”.
Q10exA: “Yes, but the equilibrium temperature will be very close to that of the ocean because the heating process depends on both the temperature difference and the mass, which is very big in the case of the sea”.
Q10exB: “Yes. The equilibrium temperature of the system can be predicted by using the following formula, in which we may assume as infinite the mass of the ocean and find an equilibrium temperature essentially equal to that of the ocean”.

Q11peA: “Ans_a) because the cool body warms more slowly in case of blowing air at ambient temperature”.
Q11peB: “Ans_b) because the fan removes the cold air in contact with the object”.
Q11deA: “Ans_b) because of the greater energy exchange”.
Q11exA: “Ans_b) because forced convention accelerates heat exchange”.

Q12peA: “Ans_c) because I have never experienced this phenomenon before”.
Q12peB: “Ans_b) because the object is in vacuum, not in air, which is a conductor”.
Q12deA: “Ans_a) because of the cooling by conduction through the supporters of the object”.
Q12exA: “Ans_a) because heat flows by radiation from the hot body to the container”.

Q13peA: “The room with the lower-positioned window should be fresher because I experienced this phenomenon in my house”.
Q13deA: “The room with the higher-positioned window should be fresher because the heat in a room tends to move upwards and gets out of the room more easily”.
Q13deB: “By assuming the same amount of radiation passing through the windows, the two rooms are equally heated”.
Q13exA: “Convective motions will push the hot air upwards in the room and the higher-positioned window will facilitate its escape, by letting the room fresher”.
Q13exB: “The room with the higher-positioned window should be fresher because hot air is characterized by a lower density and tends to move upwards and gets out of the room more easily”.

Q14peA: “Because the first is the floor where people spend more time”.
Q14deA: “Because the second floor is the higher and directly exposed to the Sun”.
Q14deB: “Because the central floor is more insulated and heat remains trapped”.
Q14deC: “Greater air pressure at the same volume, therefore higher temperature (perfect gas formula)”.
Q14exA: “Since the first floor has an exposed surface lower than that of the second one, the first floor can be the warmest only in the case of an external temperature lower than that of the inside”.
Q14exB: “The situation described in the text should correspond to a winter season, in which much more cold air, at higher density, is present at the ground floor and the second floor exchanges more heat with the colder exterior because of a greater exposure surface”.

Q15peA: “Because heat tends to move upwards”.
Q15deA: “Because the highest floor is more exposed to solar radiation”
Q15deB: “Because hot air tends to move upwards”.
Q15exA: “Because of both greater irradiated surface and internal convection”.

APPENDIX C: TEACHER ANSWERS TO INTERVIEW

1. What do you think the students should gain from the participation to a physics experiment?

   1.1 Pre-activity answers:

1.1*a*: *The students should be able to verify physical laws and formulas and how physics actually "works".*

1.1*b*: *The students should learn that we must first listen to what the Nature suggests us, and then build or use physical laws.*

1.1*c+d*: *The experimental work is a fundamental part of the scientific method. An important aim of the laboratory work is that students can learn how to write a short report that clearly describes and explains their results.*

1.1*e*: *Besides the obvious advantage to gain confidence with experimental methods, in a laboratory students can learn to cooperate with peers. This is an important skill that can be learnt in a laboratory.*

   1.2 Post-activity answers:

1.2*a*: *A physics experiment can help the students to really understand what the physical laws mean, and how they are built. The inquiry activity we experienced on the topic of thermal radiation taught me that a well conducted experiment should also help the students to improve their reasoning skills.*

1.2*b*: *In my opinion, students querying the Nature by means of physics experiments can learn how to develop a meaningful conceptual knowledge and problem-solving abilities.*

1.2*c*: *We have seen that a physics experiment can lead to many results, sometimes also unexpected. I think that practical activities in laboratory and inquiring the Nature can really help the students to learn how physicists work and behave, also in unexpected situations.*

1.2*d*: *Before this inquiry activity on thermal radiation I was convinced that the main aim of an experiment was to prepare a written report, clearly describing the aim, methods, measurements and conclusions of the experimental work. I am still convinced of the usefulness of this procedure, but now I understand that, limiting to this, students probably only develop memory or operative skills. The final aim of an effective science education should be, instead, the development of reasoning capabilities, something that can be achieved by concentrating the attention more on activities like planning investigations, making hypotheses, interpreting and discussing data.*

1.2*e*: *The peer-to-peer interaction during the development of a physics experiment can really improve student understanding of science. The various phases of the inquiry process that we discussed during the OI workshop focused well on this aspect. I mean, debating with peers, searching all together for information in books or on the internet, presenting the results to colleagues and trying to convince them of their validity are all aspects of a well conducted physics experiment that can really improve student understanding of physics.*

2. How do you think an experimental activity in laboratory should be organized in order to provide an efficient learning environment?

   2.1 Pre-activity answers:

2.1*a*: *The teacher should explain in advance to the students what they are going to observe in laboratory. In my experience, for the students this is a good way to make the most of the time spent in laboratory.*

2.1*b*: *I experienced that if the students don't know what to do, then the time spent in laboratory is fruitless. So, students should plan the experiment before entering the laboratory, trying to anticipate the results they should obtain. Then, they must collect data, explain them and compare the results with their forecasts.*

2.1*c*: *The teacher should provide the students with an instruction sheet to be followed during the experiment... I mean, a guide that can suggest the students what to do and observe during the experiment phases, and the data analysis that is best performed for the experimental aims.*

2.1*d*: *A good way to organize a laboratory activity is to have teacher and students searching together for information about the experiment before they enter the laboratory. Then the students can develop* *their experiment by following well defined steps, typical of the scientific method. Here, the teacher role is to help students to find the right way to conduct the experiment, so to minimize the waste of time.*

2.1*e*: *Students should use the hours in the laboratory to explore the physical world. This can be done by both verifying studied laws and trying to build new ones, concerning situations that were never theoretically presented them before by the teacher. An example of this latter approach can be the study of what happens to a spring when it is vertically suspended to a bracket and different weights are applied to its free end. By performing this experiment, the students can try to understand which law is governing the spring behavior.*

2.2 Post-activity answers:

2.2*a*: *Well, I understand that focusing the laboratory activity to more or less open investigations can be very interesting and stimulating for students. However, I am still convinced that in many real-school situations students should be prepared by the teacher to what they are going to observe during the experiment.*

2.2*b*: *The inquiry path we experienced here showed me the importance of the teacher work to organize different kinds of laboratory activities, all oriented to let the students to discover how the world works. The conduction of inquiry-based activities can surely help the students to understand that a researcher follows an inductive method to query the Nature, planning his/her investigation and searching for the best instruments to find answers to his/her questions.*

2.2*c*: *The inquiry-based approach represents a very good way to organize an efficient learning environment. Before this OI experience, I never had the opportunity to try a similar approach. During the few laboratory courses I attended at university, the typical aim was to verify a well established, already known, physical law.*

2.2*d We have seen that formulating questions to answer an experimental problem, planning investigations, collecting and discussing data and facing unexpected situations can be a very good method to improve the student's understanding of the nature of science. On the other hand, I'm afraid this approach could be rather dispersive, especially for students not used to work in such a way.*

2.2*e A good method to organize an experimental activity is to let the students discuss, in small groups, a given problem, formulate questions, make hypotheses, search for possible answers by using different sources of information and collect data. After this, students can try to explain their results, discussing them in a peer-to-peer working set and building a report that can be presented to classmates and to the teacher.*

3. Which is your first thought when a mismatch between the collected data and what expected from a physics theory is observed? What do you think should be done in such cases?

3.1 Pre-activity answers:

3.1*a I always try to prepare in advance the experiments I will show to my students. The main reason is to avoid any unexpected result that could bring about to uncomfortable situations of uncertainty or introducing new concepts not directly related to the experimental aims.*

3.1*b I think it is the teacher duty to avoid an experiment leading to results that do not meet the physics laws previously studied. In fact, such mismatches could generate confusion in students' thinking.*

3.1*c*: *The experiment is useful when it aims at verifying a physics law theoretically studied. For this reason a good planning of the experiment is necessary, in order to avoid unwanted effects that could distract the student's attention from the desired learning goal.*

3.1*d*: *I usually try to set up simple experiments I can easily manage. When some unexpected mismatch between data and theory is observed I generally say that the experiment failed because something went wrong and ask them to find the possible causes of the error.*

3.1*e*: *The planning phase of an experiment is fundamental to avoid unexpected results. However, sometimes it could happen to face such a situation. This occurrence should not be considered a priori a negative aspect of an experimental activity because this latter could highlight the need to deepen physics concepts not fully understood.*

3.2 Post-activity answers:

3.2*a*: *Well, I think that in some cases, when, for example, the students have already deeply studied the basic concepts, a mismatch between data and theory could be useful to observe how students behave and reason in front of unexpected situations. However, I also think the teacher should not let the student be completely free to explore because unexpected results could be inexplicable, even to the teacher.*

3.2*b*: *Actually, I think the real world is more and more complex with respect to any simple physics model. Probably, a mismatch between data and theory could be useful to highlight the basic processes of the scientific method. However, I believe that this approach is too much time consuming for our today learning schedules. Moreover, I'm not sure of the benefits the students could get from observing a disagreement between data and theory with respect to the uncomfortable confusion it generates in them, without a guide of a well experienced teacher.*

3.2*c*: *Well, I think that in many cases it could be useful for the students to face unexpected results, even if not in accordance with the studied theory. This could be useful to make the students aware of the procedures the scientists use to explore the Nature and create new scientific knowledge. This activity, however, would require a great cognitive effort from the students and long experienced teachers.*

3.2*d*: *Generally, I prefer to arrange the experiment in such a way that the results can be easily explainable by means of the studied theory. I think experimental results not matching with the known theories could help the teacher to stimulate the students to understand how scientific knowledge is created, but the teacher should always be clear and not show uncertainty.*

3.2*e*: *I believe the experimental activity should aim to observe and assess the students' reasoning skills. In this view, it is important to place the students in front of unknown situations, although such events could result new even to the teacher.*

4. When you introduce a new physics law to the students, which aspects do you consider important and in need to be explicitly highlighted?

4.1 Pre-activity answers:

4.1*a*: *A physics law is a natural rule governing the universe. All physical phenomena follow these laws and the scientists' work is to discover such universal rules. All physics laws are expressed by mathematical equations, so it is a fundamental job for the teacher to explain the students how to manage such mathematical expressions.*

4.1*b+c*: *A physics law is a mathematical expression that we can use to solve physics problems, or to make predictions, as in the case, for example, of calculating the motion of an object. I believe it is important to stimulate the students to consider the relationships between different physics laws and the dimensional analysis.*

4.1*d*: *When dealing with the study of a new physics law, I usually introduce it to the students by focusing on the physical quantities that can be measured.*

4.1*e*: *A physics law represents a well established theory regarding the functioning of the universe. We use the physics laws to understand how the world works and teach it to the students. I generally use to show some examples and applications of the studied physics law in order to help the students to store that content in their long term memory.*

4.2 Post-activity answers:

4.2*a*: *A physics law is a mathematical representation of a natural rule governing the universe. I think an important aspect is represented by its mathematical formulation and its graphical representation as a function of the main quantities involved.*

4.2*b*: *A physics law is a mathematical expression that is created by the scientists to describe the observed phenomena. I have always considered fundamental to introduce the students to the theoretical framework in which the physics law is developed and also to focus on its mathematical limitations. However, this OI experience taught me how much impressive and effective the experimental activities may be.*

4.2*c*: *In some cases it can be easier and probably more fruitful to let the students to "discover" the law by themselves by means of experiments and, in this way, achieve a better understanding of its applications.*

4.2*d*: *A physics law is a well established expression that provides the opportunity to describe the observed phenomena. For this reason, I think that a good method for introducing the students to a new physics law can be practiced by showing its experimental applications. In this way, it is possible to better understand the role played by each variable.*

4.2*e*: *A physics law is a mathematical simplified view of the real world, which is a very complex system and very difficult to be understood in its totality. Scientists continue to explore the universe to find more accurate descriptions and refine the already known physics laws. During this experience, I realized how much important the experimental validation of a physics law can be, for what concerns, in particular, the understanding of approximations and limits of validity.*

5. When you plan an experiment, how do you take into account the environment surrounding the system you want to study or external factors that may play a role in the results?

5.1 Pre-activity answers:

5.1*a*: *I think I have never taken into account the surrounding environment or external factors during an experiment carried out in the lab.*

5.1*b*: *Well, I have rarely considered the influence of the surrounding environment on my laboratory activities. If I take my experiment under control, I don't need to consider any external effect.*

5.1*c*: *I'm aware that some external factors could affect the measurements we do during an experiment, for example because of a distraction on executing the procedure. In this case, we will introduce some casual errors in our data. I also know that some systematic errors can be introduced into the measures, sometimes due to the instrument used to collect the data. So, I usually try to avoid distractions and check the instruments' calibration.*

5.1*d*: *I have never minded about external factors, probably because I have never needed to consider them before.*

5.1*e*: *In my practice of an experiment I have rarely faced with the need of considering the effects due to external factors, because I always taken into account all possible sources of errors, by including them in the data statistics.*

5.2 Post-activity answers:

5.2*a*: *During the workshop we have personally experienced the importance of taking under control the boundary conditions of an experiment. Now I have figured out how much important it could be in some cases.*

5.2*b*: *Actually, external factors could be present and affect your measurements. We definitely should be more accurate to continuously check if any deviation is observed with respect to what expected.*

5.2*c*: *Well, I guess external factors that could play a role in experimental activities are always present in laboratory. In some cases such effects may cause the failure of an experiment, but sometimes they can be the boost towards the development of new ideas and a deeper understanding of the observed phenomenon.*

5.2*d*: *When I'm involved in a physics experiment, I'm so focused onto my measurements that I often forget to take care of external effects. Instead, I think every teacher should strive to consider the surrounding environment an important part of their experiment.*

5.2*e*: *Well, I think that it is not so easy to consider all the external factors affecting an experiment. Fortunately, most of the times they probably have negligible effects.*

6. What do you think about students' working in groups?

6.1 Pre-activity answers:

6.1*a*: *Students should always work in very small groups, or individually if the laboratory allows this. They should try to collect data and make sense of them relying only on their own resources.*

6.1*b*: *I think that working in small groups is useful for learning. The most capable students can help classmates to understand what the teacher is saying.*

6.1*c+d*: *Working in groups can allow students to compare ideas and results they obtain in exercises and laboratory experiments. I think that peer-to-peer interaction is an efficient way to learn.*

6.1*e*: *As I said before, in my classes I often suggest students to work with classmates, in order to collect information on a given topic and exchange ideas.*

6.2 Post-activity answers:

6.2*a*: *I still think that students should work in very small groups. However, I acknowledge that group-work can be useful to improve the interpersonal skills of students and their capacity to share data and communicate results and information.*

6.2*b*: *I am convinced that to train students to work with classmates can allow them to understand how people work in industry or research teams. In a group every student can contribute to the final result with his/her own skills. Moreover, the communication skills are strengthened in a peer-to-peer environment, where a student does not need to be afraid of what he/she is saying with respect to the discussed topic.*

6.2*c+d+e*: *Students can gain a lot from group work. Many researchers work in more or less large groups. In them, everyone has something specific to do and all share the data and build explicative models.*

7. Do you usually provide your students with all the information they need to carry out the experiment or do you allow them to even access to other sources (for example from libraries, web-based data or simulations, etc.) for additional support? What do you think should be the advantages or disadvantages of such practice?

7.1 Pre-activity answers:

7.1*a*: *I usually provide the students with all the needed information for carrying out the experiment and sometimes even the expected results. I don't think the students can usefully access the web to search for further information because they don't have enough investigative autonomy.*

7.1*b*: *When the experiment is performed as a mere demonstration the students do not need to use further resources of information. On the other hand, when the aim of an experiment is to show to the students the discovery of a new physics law, I allow the students to personally check the results with data published in books or websites.*

7.1*c+d*: *The web-based resources could be too much dispersive and generate confusion. I prefer the students use the textbook and my personal notes, which I believe are sufficient.*

7.1*e*: *Well, I think the web could be a useful resource of information only if the students are appropriately guided. I acknowledge that some web-based simulations may be useful to improve the understanding of tough concepts, but I have never included them in my teaching practice.*

7.2 Post-activity answers:

7.2*a+b*: *In physics web-based resources are very large and extremely diversified. This makes difficult for the students to perform a useful selection, even considering the opportunity to get a wider view of the concepts and to improve their critical abilities. However, an appropriate guide is necessary and, probably, even a limitation of the available resources.*

7.2*c*: *I found very stimulating the reading of some research papers about the physics concepts to be experimentally investigated, just because some textbooks report only the physics law with its explanation and do not clarify how it was discovered or can be verified in laboratory. Many research papers contain a method section whose reading can be very useful both to teachers and students to obtain a more comprehensive view of the processes underlying the search for a physical explanation of a given phenomenon.*

7.2*d*: *The use of resources from the web can be effective for students in their final or penultimate year of high school who have achieved a high degree of autonomy in their study. In addition, the students' preference for computing resources generally facilitates the approach to problem solving.*

7.2*e*: *Web-based information can be useful, especially when the students have to understand results that apparently cannot be explained. This activity, however, requires to the students a considerable* *amount of time. Unfortunately, it happens very often that at school we do not have the necessary time to carry out a teaching/learning path with these characteristics.*

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