An Investigation of an Independent Learning Approach in University Level Chemistry:

The Effects on Students' Knowledge, Understanding and Intellectual Attributes

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Abstract

The aim of this study is to provide a preliminary insight into a teaching strategy which deploys independent learning in degree-level chemistry. For this purpose, the impact of the teaching approach applied in a Macromolecules course on students' knowledge of, understanding about chemical ideas, and intellectual attributes was investigated. To achieve this, diagnostic questions both before and after the teaching, descriptive questionnaires and standardised interviews were used.

The sample consisted of first-year undergraduate students who took the Macromolecules course in the Department of Chemistry in one of the top ten universities in the UK. In total, one hundred sixty-seven students took part in the study and interviews were carried out with twenty-four students.

The results revealed that the independent learning strategy applied in the Macromolecules course can be effective in improving students' knowledge of and understanding about chemical ideas, as well as contributing to some of their intellectual attributes. It was also found that when students were left on their own to do independent investigations, without any support, their knowledge of and understanding about chemical ideas from the course content did not change statistically significantly. In addition, whilst there was no statistically significant change in student responses with a sign of misunderstanding for nine out of ten diagnostic questions, in one case there was statistically significant increase in the number of student responses with a sign of misunderstanding.

The results of this research study also presented a detailed and personal picture of students' views of the independent learning approach. Student arguments for their appreciation and disapproval of the strategy were revealed and discussed.

The findings of this research study can offer a supplementary resource for teachers at tertiary level to use in situated ways when dealing with similar course contents and similar learning objectives which they encounter during their practice.

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Author's Declaration

I hereby declare that this dissertation is a record of the research study carried out in the Department of Education at the University of York during the period from October 2010 to January 2014. The dissertation is original in content except where otherwise indicated and the work in this thesis has not been previously submitted for award at this or any other institution.

Chapter 1: Introduction

1.1 Background and Motivation

Thinking about my first lecture as a student, I can still remember what a tragic experience it was. I was with over 100 students in a cold and big amphitheatre, thinking about my choice of university while everyone was waiting for the lecturer. The lecturer was talking formulae as he came in, and for one and a half hours he scribbled them on board as he talked and everybody was trying to note them down in a rather nervous manner to keep up with his dictation. With a quite naïve idea I was attributing this experience to one particular lecturer, however other lecturers proved my hypothesis false. So, I decided to attribute this teaching experience to this particular university in which I studied for my BSc. However, my discussions with friends who were studying in different universities made my aware that this was a fairly common experience for the overwhelming majority of university students. I spent four year in the course, hoping that my lecturing experience would change, but I graduated and all the lectures were the same with only a handful of exceptions. I finished my degree with the idea that someone should do something to change this didactic experience of lecturing as it was not effective from my personal point of view.

Ironically, my first official lecture experience as a teacher was not much different from my first lecture experience as a student. I had to solve some practice questions to prepare students for their final exams. Particularly due to my lack of confidence, I had prepared forty pages of notes in advance. I entered the room, wrote the questions on the board and answered them on my own.

This kind of iterative cycle of education system made me think about the quality of teaching experience in higher education. I began to ask to myself what proportion of the things that I had learned during my education I still remembered and used in my work and life. My conclusions implied that I could neither remember nor use very much of my knowledge of chemistry that I had learned during my university education. More importantly, I was continuing to gain new knowledge and to adopt new intellectual attributes. That situation led me to think about teaching approaches that focus on learning how to learn, as well as covering understanding of the key ideas of the discipline rather than those which are didactic and merely focus on knowledge acquisition.

Moreover, discussions with my students about their interest in chemistry revealed that many students lose their interest in chemistry as they believe that a university education does not provide what they will be asked for in the workplace after their formal education has finished. When I asked students to solve numerical problems, they could solve them by using some algebraic methods, but most of them were unaware of the understanding behind the problems. This situation was similar to the findings of Sawrey (1990).

When I discussed the issue with other lecturers in the department, I realised that lecturers usually find themselves in a paradox. Whilst they often argue that in university education particularly they should encourage students to develop their own point of view within a subject, to be critical and not to accept ‘spoon-feeding’, they none the less expect the right answers. No matter how democratic they are about respecting the student’s point of view, there is usually a pre-defined standard answer. That is why, I observed, university education is often didactic. Many lecturers do not simply think that students are just puppets who should repeat the correct answers after their lectures. From my experience, this is also a model that university lecturers strongly resist, at least in theory if not in practice. Many educators are well aware of the joy which learners get from exploration and discovery on their own and the impact of it on their learning experience. However, they usually seem to find themselves in a dilemma of either applying didactic teaching to assume that all students will learn the same thing or promoting students’ independent learning which makes learning something personal and peculiar to that individual, and therefore not so amenable to mass treatment. In my opinion, an important point which is often missed in this argument is that although independent learning in many ways assures that each student achieves learning on his or her own, traditional didactic teaching does not assure that all students learn the same thing.

Preliminary research around this topic exposed the fact that these concerns are not ignored. There is an ongoing discussion about what scientists want to teach their students and how to teach it (Talanquer & Pollard, 2010). Do we want our students to know what we know, or do we want them to understand how we think? Increasingly, the internet age is having a dramatic effect on the requirements of science education. Particularly in the past, retrieval of information created a difference between scientists. Before the internet, scientists had to spend quite a lot of time in searching for information from other sources. This required time and there was therefore a significant advantage in having as much knowledge as possible in your head. However, with the internet, typing a query into the right search engine will now return the required information almost effortlessly. This situation again raises the question of whether traditional didactic lectures which usually focus on increasing students' subject knowledge are the most beneficial teaching approach in higher education.

Considering this discussion today, emphasis on knowledge is getting smaller and the balance is shifting towards the adaptive abilities, eagerness to learn and learning how to learn, which give a much greater readiness for a career in our swiftly changing world (Schwartz, 2007). This does not simply mean that we should give up the aim of improving students' understanding of chemical ideas and only pay attention to those attributes, but it does go without saying that those attributes should be considered as an inseparable part of a complete education.

The educated man as described by Carl Rogers (1969, p.169) is

The man who has learned how to learn; the man who has learned how to adapt and change; the man who has realised that no knowledge is secure, that only the process of seeking knowledge gives basis for security.

Furthermore, one of the essential claims of university education is that everybody can pursue their own personal way of learning. All the traditional equivalents of university education have similar aims, such as stimulating people's idiosyncratic ways of learning or allowing or triggering learners to study further than the basic study activities required by the curriculum which is not very likely to occur in traditional didactic lecture environments.

This requires students to take responsibility for their own learning, where they use the university as a set of resources largely under their control. A community of scholars pursuing their own course towards knowledge and enlightenment, inspired but not directed by their lecturers, seems to be the most attractive vision of academic learning. However, students do not become part of this community on their own. It requires some abilities for students to be independent learners who have learned how to learn and do not require to be directed and these abilities should also be the focus of university teaching as well as understanding about key ideas.

One possible way of improving students' independent learning abilities is to apply teaching approaches which aim to promote independent learning. More research needs to be done to identify what sort of independent learning methods are used in practice and what are the implications of these practical applications on learning. The results are important both for improving the quality of teaching and for developing the theory of instructional strategies which aim to promote independent learning. Hence, it has been concluded that it is worthwhile to conduct a research study into the impact of a teaching approach which aims to promote independent learning at tertiary-level chemistry education.

1.2 The Purpose of the Research and the Research Questions

The purpose of this research study is to identify the effects of an independent learning approach on students' learning of chemical ideas such as recycling, intermolecular bonding, polarity, isomerism and combustion reactions, together with their intellectual attributes of scientific reasoning, creative thinking and self-assessment. For this purpose, tests with diagnostic questions (both before and after teaching), questionnaires and structured interviews (both after teaching) were used. The study was undertaken in the UK with an entire cohort of first-year chemistry students as respondents. The findings of this study are intended to be used to develop effective teaching methods which aim to promote independent learning in chemistry education at tertiary level, as well as contributing to the related literature on independent learning approaches.

In addition, many educational centres, including universities and colleges, are attempting to provide more effective, student-centred instruction, to find creative and cost-effective ways to deliver courses, and to motivate students in order to decrease dropout from classes and degree programmes (Clark, 2009). The investigation of instruction strategies has great potential to improve teaching and learning. It has the capacity to help teachers to guide students in the construction of meaning which is closer to that 'agreed' by scientists (Garnett, Garnett & Hackling, 1995). In the literature review (*see* Chapter 2), it is concluded that the vast majority of the literature that shows the benefits of independent learning are from complex teaching approaches, which makes it hard to attribute all these mentioned benefits to independent learning itself. It is concluded that more research needs to be done in order to have a better understanding of teaching approaches which aim to promote independent learning at tertiary level. This research study aims to investigate the impacts of a teaching approach which does not include any lectures and primarily relies on students' independent learning. Hence, it can be claimed that findings of this research study can be attributed to independent learning itself. In order to measure the impact, first a baseline needed to be set to monitor the changes in students' levels of knowledge, understanding and intellectual attributes. Therefore, the first research question is:

1) What level of knowledge, understanding and intellectual attributes do beginning undergraduate chemistry students have in relation to a Macromolecules course's content?

Having established a baseline, the next objective was to determine the ways in which students' learning was influenced by the independent learning strategy used in the Macromolecules course. The second research question is therefore:

2) How are students' levels of knowledge, understanding and intellectual attributes influenced by the independent learning approach?

Another significant conclusion from the reviewed literature is that little research is available about the students' and lecturers' views of independent learning. In an attempt to fill the recognised gap in the literature and to gather information which could then be used to improve the practice of independent learning approaches, students' and lecturers' views and their experience of the approach needed to be investigated. Therefore, the third research question is:

3) What are the students' views and experiences of the independent learning?

1.3 Definition of Terms

Before proceeding, it is necessary to reflect on the wide range of words that have been included under the rubric of independent learning and have been used in this research study.

1.3.1 Independent Learning

Independent learning is defined as that learning in which the learner, in conjunction with relevant others, can make the decisions necessary to meet the learner's own learning needs (Kesten, 1987). Although this definition comes from an almost thirty-year-old source, it has been accepted and used by many recent scholars who have studied independent learning (*see* Bates & Wilson, 2002; Black, 2007; Bullock & Muschamp, 2006; Laurillard, 2013; William, 2003). Hence, in this research study the definition made by Kesten (1987) is accepted and used as the definition of independent learning.

1.3.2 Misunderstanding and Intellectual Attributes

Understanding is a complex phenomenon (Nieswandt, 2007), described as the ability to apply existing knowledge in a range of novel situations (Darmofal, Soderholm & Brodeur, 2002). Using, adapting and changing knowledge is necessary for understanding (Claesgens, Scalise, Draney, Wilson & Stacy, 2002). On the contrary, misunderstanding refers to an idea that it is scientifically incorrect or unacceptable. It has been reported that there are over twenty different terms used in the literature to refer to students' scientifically incorrect or unacceptable ideas, to misunderstandings (Millar, 1989). The most common are 'misconceptions' (Gil-Perez & Carrascosa, 1990; Hackling & Garnett, 1985), 'children's ideas' (Gilbert, Osborne & Fensham, 1982), 'alternative conceptions' (Garnett *et al.*, 1995), and 'alternative frameworks' (Driver, 1981). There is general agreement that the word ‘misconceptions’ has been used inappropriately in research in this area (for example, Gunstone, 1989). In this study, the term ‘misunderstanding’ is preferred and used.

Similarly, the idea of a skill has become bigger, broader and much fuzzier around the edges during the last two decades (Warhurst, Grugulis & Keep, 2004). Moreover, it appears that nowadays, skill appears to be a more subjective phenomenon than ever. Kuhn, Amsel and O’Loughlin (1988) claimed that ‘skill’ is usually a vague or ill-defined concept in the domain. Considering that skill is a quite vaguely defined and wrongly used idea in the literature, in this research study ‘intellectual attribute’ is the preferred term and it refers to a feature that it is hoped the well-educated person will possess as s/he emerges from the education system.

1.3.3 Chemical Ideas

In addition, there is also little agreement among experts about the definition of a ‘concept’. In general, it is used synonymously with ‘idea’ (Herron, Cantu, Ward & Srinivasan, 1977). However, the word ‘concept’ is more appropriately applied to a fundamental idea which underpins much of the knowledge and understanding in a subject. In chemistry such ‘concepts’ might be chemical change, conservation of mass or the particulate nature of matter. Because of the disagreement among the experts about the definition and use of the term ‘concept’, in this research study, the term ‘idea’ is preferred. It refers to chemical terms such as recycling, intermolecular bonding, polarity, isomerism and combustion reactions.

1.4 A Summary of the Forthcoming Chapters

This section offers a brief description of what is to be expected in each of the following chapters. The intention is to make this study easily accessible to the reader, as well as to provide some basic orientation through the overall research subject, by presenting a general overview of the structure and content. The study is divided into eight chapters.

This first chapter presents the research background and motivation, provides the main aim and defines the terms used in this thesis. It also identifies the research questions. It gives brief information to the reader about the main motivation behind the study and the reasons for studying this subject as a research topic.

The second chapter focuses on the recent research trends in science education in general and provides information about the reviewed literature on independent learning and the teaching approaches which aim to promote independent learning in higher education. The chapter is set out to describe the origin and current use of the independent learning approach whose principles have been applied to create the teaching approach investigated in this research study. Moreover, it outlines the research related to students' understanding of chemical ideas and students' intellectual attributes.

The third chapter focuses on the context of the study. It has three main purposes. First, this chapter aims to present the rationale behind the shift from traditional teaching approaches to independent learning methods in tertiary-level chemistry education. Second, this chapter aims to map the Macromolecules course's teaching approach against the literature reviewed in the previous chapter. Finally, it aims to explain fully how the Macromolecules course was identified and why it was chosen as the focus of this research study. With those key features, this chapter is crucial for the understanding and further application of the investigated teaching approach and the clarification of this research study.

The fourth chapter covers the methodology of the research project, describing the theoretical backgrounds of the research methods that were employed in the research and explaining the preparation of the research materials and their piloting.

The fifth and sixth chapters report the results of the student tests. Chapter 5 analyses the pre-intervention results of the students and their answers to the diagnostic questions. This chapter sets the baseline for evaluation and gives information about the level of knowledge, understanding and intellectual attributes of the sample students. Chapter 6 then analyses the post-intervention, after the Macromolecules course, responses to the diagnostic questions. This chapter offers a comparison between the pre- and the post-intervention results.

The seventh chapter reports the data which were collected from the questionnaire and interviews with students in order to reveal their views and experience of the independent learning approach. These three chapters, Chapters 5, 6 and 7, present the findings of this research study.

The eighth and concluding chapter describes the outcome and conclusions of the study. It offers a summary of the results as well as an evaluation of the research. Ultimately, based on the conclusions drawn from the previous chapters, it discusses the results and offers contributions to knowledge. This final chapter also includes a detailed critique of the study.

Chapter 2: Literature Review

Introduction

This chapter is intended to provide a theoretical framework for this research study. There are two main parts to this chapter; the first defines the context and focus of the study as well as synthesising the literature on independent learning, particularly focusing on tertiary level education. The second part is concerned with providing an overview of the research related to students' understanding of chemical ideas and students' intellectual attributes in order to provide a better understanding of what has given rise to the issues that will be further discussed later on, in the following sections and chapters.

The chapter will describe the origin and current use of independent learning whose principle has been applied to create the teaching approach investigated in this research study. It includes an overview of the current movement to change higher education through a range of innovations, focusing particularly on the science education context. This chapter explores the body of literature discussing a range of teaching innovations such as project-based learning, problem-based learning, moving in-class modules online, flipped classrooms and the promotion of independent learning through ICT which are relevant to the aims of the course studied. Furthermore, it discusses how those research areas are feeding into current teaching practice in science education at tertiary level. It is important to contextualise this study within the literature about teaching innovations in higher education that move away from traditional lectures and which have similar educational aims to the course explored here. Finally, the chapter concludes with a suggestion of examining how the impact of teaching strategies which have similar educational aims can contribute to the improvement of both the practice and the theory of these innovative approaches to teaching science in higher education.

2.1 The Case for a Change from Traditional Instruction

Nowadays, a low level of interest in science subjects by students, especially when they have an option to choose to study these subjects, has been established in the literature. The reasons which lie behind chemistry's lack of popularity vary, and include the perceived intrinsic difficulty of the subject, the absence of well-qualified teachers, the negative attitudes of society towards science and scientists (such as that science is dangerous and it creates problems), the relatively expensive structure of science teaching and science practical applications, and gender issues (Bennett & Hogarth, 2005; Osborne & Collins, 2001). However, in more depth, in an attempt to find the roots of the problem, it is necessary to investigate the first-hand experiencers of the situation, school students. Some comments by students when asked about their views on science courses were

- *There's one answer and you've got to learn it.*
- *It's just not as creative as English.*
- *In art and drama you can choose, like whether you're going to do it this way or that way, and how you're going to go about it, whereas in science there's just one way.*

(Osborne & Collins, 2000)

These statements were all made by pupils, and further investigation supports the robustness of negative attitudes towards school science (Bennett & Hogarth, 2005; Cerini, Murray & Reiss, 2004; Haste, 2004; Jenkins & Nelson, 2005). Unfortunately, negative attitudes towards science are not only limited to school science and are not only found among school children but also among all levels of society. As Snow (1964, p.20) explained from his personal experience,

A good many times I have been present at gatherings of people who, by the standards of the traditional culture, are thought highly educated and who have with considerable gusto been expressing their incredulity at the illiteracy of scientists. Once or twice I have been provoked and have asked the company how many of them could describe the Second Law of Thermodynamics. The response was cold: it was also negative. Yet I was asking something which is about the scientific equivalent of: 'Have you read a work of Shakespeare's?'

As it would be quite normal and fair to expect an educated person to know some work by Shakespeare, so it should be equally normal and fair to expect an educated person to know about the fundamental principles of the world in which he/she lives. However, bearing in mind the researches which will be described in the following sentences, it is not sensible to hope that chemistry would be appreciated as much as Shakespeare's beautifully written plays. The way that chemistry is being taught has been the same traditional, didactic way for decades until very recently, and there is a resistance to changing traditional teaching approaches (McRobbie & Tobin, 1995). Generally, educators have focused on covering the expectations of the curriculum, which often involves well-structured problems, recipe-style-learning laboratory work, and tightly-timed learning activities for a necessary piece of knowledge (Gabel & Bunce, 1994; Hobden, 1998; Shymansky, William & Alport, 2003; Walberg, 1991). It seems that chemistry education has reached a stage that some educators have missed the point of learning and teaching chemistry in the first place. As has been discussed by numerous scholars such as Schwartz (2007), chemistry education strives for, or should strive for, conceptual understanding, excellence in the related skills, awareness of practical, social and ethical applications and issues, and some information about the archival roots of chemistry and its place in the broader intellectual tradition. It is not hard to claim that traditional teaching methods usually fail to achieve any of these merits of chemistry education. One possible reason behind this failure could be the attempts of traditional methods to convey a particular piece of information instead of attempting to improve students' understanding in general. This situation may be associated with the famous proverb that says: 'Give a man a fish and you feed him for a day; teach him how to fish and you feed him for a lifetime'. In this case, traditional lecture-based teaching styles can be seen as giving students a fish, however; the need is to teach them how to fish. This situation stimulates scholars in the education domain to create and apply innovative teaching approaches which have a particular focus on independent learning mainly because they aim to develop skills and strategies that will allow learners to continue learning and improving long after they finish their courses. They offer to improve students' autonomy and they may be a better solution to the current problems of science education than traditional instruction strategies.

2.2 Recent Research Trends in Science Education

The issues raised by a number of significant scholars in the domain have resulted in numerous attempts to improve the shortcomings described in the preceding section, such as covering only well-structured problems or aiming only at the acquisition of a necessary piece of knowledge in today's science education curriculum. A first glance at the literature makes it clear that curriculum change and the use of multiple instructional strategies to improve understanding were two main areas of focus in science education research over the last twenty years (Hurd, 2002; Kelly & Anderson, 2000). Even though significant changes in the anecdotal responses of students have been observed, it would be too optimistic to claim that these attempts achieved their ultimate goal. The majority of students nowadays are still too far away from satisfaction. One possible reason behind this could be the lack of long-term improvement since the impacts of the interventions were usually not longitudinal but were context- and facilitator-dependent rather than being permanent and less dependent on personal variables. These results stimulate science educators to continue creating and applying innovative teaching approaches. What follows is a review of two main areas of focus in science education research and a discussion of the rationale for independent learning as a theoretical framework.

In terms of curriculum change, one of the most dominant styles during the last two decades has been the context-based science teaching approach. Attempts have been made to adapt the context-based approach to all stages of chemistry education but the majority of these attempts have been in the secondary and upper-secondary levels of chemistry education. Nowadays, science curriculums which are shaped by context-based education are being used in many countries such as the UK, the US, Germany, Holland, Russia and Turkey. Context-based chemistry teaching can be described, in its most basic form, as teaching chemical principles and ideas in a way which relates them to students' everyday life experiences. Three main aims of context-based education, particularly in higher education settings, can be discerned: to provide students with more interesting lectures, to improve the science learning process by increasing the engagement which is stimulated by the increased interest in science and lectures, and to provide scientifically literate people who can make sense out of some of the science which is related to their everyday lives (Bennett &

Holman, 2003). Innovative context-based approaches and materials have been designed, applied and assessed intensely over the last twenty years. The literature is replete with positive statements by students and the majority of the studies have identified significant increases in students' interest and their engagement (Bennett, Lubben, & Hogarth, 2007; Gilbert, 2006; Gutwill-Wise, 2001; King, Bellocchi & Ritchie, 2007; Ramsden, 1997; Schwartz, 2006). However, it is not easy to see in the literature the same results in terms of the students' understanding of scientific ideas. The findings of studies related to this issue are less significant and more open to interpretation. Moreover, probably the most common criticism is that differences in the findings stem from the personal differences between teachers and from difficulties related to the extent of teacher professionalism (Vos, Taconis, Jochems & Pilot, 2010). It can clearly be seen from the literature that many professionals in the science education domain target the creation of learning and teaching approaches which aim to increase the interest, motivation and integration of young people, but at the same time, any compromise regarding the learning of the key ideas of the curriculum is seen as an unacceptable deficiency in teaching strategies. Moreover, the importance of curriculum development on learning is still an issue that is being discussed by scholars. Some researchers argue that there is no curriculum-related factor in the first ten in the descending ranking list of the impact of factors on learning (Hattie, 2011). This basically does not mean that research on curriculum development has no value; however, the relative value of this kind of research compared with other areas such as instruction strategies is open to discussion.

The second major research area in science education during the last two decades is the use of multiple instructional strategies to improve the understanding and intellectual attributes of students, to which this current research study aims to contribute. Schraw, Crippen and Hartley (2006) summarised six general instructional strategies that reflect extensive research agendas within the science education literature. These are inquiry-based learning, the role of collaborative support in learning, strategy instruction to improve problem solving and critical thinking, strategies for helping students to construct mental models and to experience conceptual change, the use of technology in the teaching and learning processes, and the impact of student and teacher beliefs on learning. It has been suggested by some scholars (Butler & Winne, 1995; Gunstone, 1999) that these six instructional strategies can contribute to the improvement of students' understanding of scientific ideas as well as to students' intellectual attributes in numerous ways if they are applied appropriately. Since the instruction strategy applied and investigated in this research study aims to promote independent learning, instruction strategies which have similar aims also needed to be reviewed. In the next section, definitions and implications of independent learning will be discussed.

2.3 Independent Learning

Independent learning is defined as that learning in which the learner, in conjunction with relevant others, can make the decisions necessary to meet the learner's own learning needs (Kesten, 1987). Although this definition comes from an almost thirty-year-old source, it has been accepted and used by many recent scholars who have studied independent learning (*see* Bates & Wilson, 2002; Black, 2007; Bullock & Muschamp, 2006; Laurillard, 2002; Williams, 2003). Hence, in this research study the definition made by Kesten (1987) is accepted and used as the definition of independent learning. Today, the concept of 'independent learning' is associated with, or part of, a number of other educational concepts and the wider policy agenda of contemporary relevance such as 'personalisation', 'student-centred learning' and 'ownership' of learning (DCSF, 2008). Independent learning has increasing significance in the UK and it is one of the essential elements of personalisation, which the government sees as vital to the continuing development of a system of particularly school education that promotes high quality and lifelong learning, and social equity and cohesion (DfES, 2006). Many schools in England and Wales identify the development of students' independent learning skills as an aim in their school development plan (DCSF, 2008). More specifically in higher education (HE), for over two decades now, there has been an extensive movement internationally to change teaching in HE through a range of innovations which promote independent learning (Laurillard, 2013).

In the literature, there is a common agreement that learners develop the values, attitudes, knowledge and skills need to make responsible decisions and take appropriate actions in regard to their own learning during the process of independent learning (Bates & Wilson, 2002; Gorman, 1998; Kesten, 1987; Williams, 2003). There is also a consensus that independent learning is promoted by enabling opportunities and experiences that encourage learner motivation, curiosity, selfconfidence and self-reliance, and is based on the understanding by learners of their own interests and a valuing of learning for its own sake. Hence, in this sense the responsibility of educators is to facilitate these opportunities and experiences. It is important to emphasize that independent learning does not simply involve giving learners more independence. Instead it involves educators thinking clearly about learning outcomes and learning stages and creating enabling environments which lead to these learning outcomes and stages (Gorman, 1998).

2.3.1 The Continuum between Independent and Dependent Learners

In the literature related to independent learning, the contrast between a dependent and an independent learner has been stressed by a number of scholars (Alexander, Rose & Woodhead, 1992; Boekaerts, 1997; Williams, 2003). Whilst the dependent learner is usually described as a passive recipient of knowledge, or what represents that knowledge, the independent learner is defined as a person who actively directs and regulates his/her own learning. Dependent learners see the educator as the ultimate source of knowledge and the expert; they accept themselves as a supplementary component of the learning process, whereas independent learners recognise that they are the learning experts for their own learning. Winne and Jamieson-Noel (2002) described the difference between the independent and the dependent learner as the ability to combine information processed and information processing without an educators' intervention. It is worth mentioning at this point that independent learning is not an absolute standard but a direction or goal to be pursued (Kesten, 1987); it is a direction for the process of education. In the literature, it is often shown that there are different degrees of independence in a continuum from the dependent to the independent learner (Bereiter, 2002; Boekaerts, 1997; Ertmer & Newby, 1996) and that educators can help learners to make some progress in their degree of independence in this continuum. It is generally accepted that each learner is at a different point on the scale of independent learning that measures between the dependent learner and the independent learner. The existence of absolutely independent learning is a topic that is still being discussed (Schunk, 2005), so the possibility and desirability of reaching that absolute standard should not or cannot be the main focus of education. However, there is a significant value in the application of teaching strategies that might help students to make some progress in their degree of independence in a continuum from the dependent towards the independent learner. The dynamic of the continuum is a shift in responsibility between learner and teacher, so that by degrees the learner assumes greater responsibility for directing his or her own learning and negotiating strategies and processes with the teacher. For movement to take place along the continuum, together with the transfer of responsibility there is assumed to be a development of particular skills (independent learning skills, *see* section 2.3.3.1) by the learner.

2.3.2 Different Terms used to Describe Independent Learning in the Literature

There are a number of different terms used to describe independent learning particularly in different countries, such as ‘self-regulated learning’ (Schunk & Zimmerman, 1994; Pintrich, 2000), ‘self-directed learning’ (Korotov, 1992), ‘learning to learn’ (Black, McCormick, James & Pedder, 2006), ‘self-directed active learning’ (Birenbaum, 2002), ‘student-centred learning’ (Black, 2007), ‘self-learning’ (Mok & Chen, 2001), ‘self-access learning’ (Chia, 2005) and ‘supported study’ (MacBeath, 1993). It is important to consider these terms briefly because of their similarities in describing independent learning. All these terms describe essentially the same themes and processes (DCSF, 2008). These themes and processes involve students having an understanding of their learning, taking over responsibility for their learning and working with teachers to structure their learning environment. This allows learners to become active participants in their own learning process (Zimmerman, 1986). It is important to stress that all the literature related to these terms claim that independent learning does not only involve learners working alone. Additionally, independent learning involves more capable others such as lecturers, tutors or peers guiding learners towards becoming more independent (Bullock & Muschamp, 2006; Allan, Cook & Lewis, 1996).

Self-regulated learning is a term commonly used in the US and it is equivalent to the independent learning which is a term commonly used in the UK. Schunk and Zimmerman (1994, p.309) defined self-regulated learning (SRL) as “the process whereby students activate and sustain cognitions, behaviours and affects which are systematically oriented towards attainment of their goals". More simply it is defined as the ability of learners to control the factors or conditions affecting their learning (Dembo, Junge & Lynch, 2006). The concept refers to a learner's ability to understand and have some sense of control over his/her learning environment. In order to do this, it is necessary for the learner to set aims, find out strategies that will help to reach those aims, implement those strategies and try to see progress towards the aims (Schunk, 1996). Learners who are self-regulated "are distinguished by their systematic use of metacognitive, motivational, and behavioural strategies; by their responsiveness to feedback regarding the effectiveness of their learning; and by their self-perceptions of academic accomplishment" (Zimmerman, 1990, p.14). In addition to those essential components, recent studies have shown that the cognitive processes which aid understanding and remembering information can be seen as additional characteristics of SRL (Wernke, Wagener, Anschuetz & Moschner, 2011).

Usually, educators are aware of the learners who make insightful comments, are well-organised and ready for the class, meet assignment deadlines, and ask for support when they do poorly in their work or struggle to understand a concept. Those students who do so may be defined as self-regulated learners. Educators are also familiar with those who fail to apply knowledge, do only enough work to get by, and persist with the same behaviours regardless of outcomes. What educators may not be familiar with is that they can influence these behaviours in positive ways. SRL has been viewed both as a set of teachable skills and as a developmental process that emerges from experience (Paris & Paris, 2001). At first sight, those two ideas can be seen as distinctly different from each other, however; they both support the argument that educators can help learners to become more self-regulated in their learning.

Similar to SRL, some scholars (Bolhuis & Voeten, 2001; Korotov, 1992) have used the term self-directed learning (SDL). According to Korotov (1992), self-directed learning allows learners to become self-disciplined and creative. Korotov also suggested that characteristics of self-directed learners involve self-monitoring and "comradely solidarity" (Korotov, 1992, p.22). SDL and 'learning to learn' are terms which can be used synonymously (Bolhuis & Voeten, 2001). Higgins *et al.* (2005) defined 'learning to learn' as a process during which learners discover about learning. This involves a set of skills that allow students to learn more effectively and therefore become learners for life.

In contrast, Birenbaum (2002) emphasized the difference between learning activities which are taken over by the teacher, and learning activities in which learners perform learning and thinking activities by themselves. He defined self-directed active learning as learning in which learners are meta-cognitively, motivationally and behaviourally active in their learning (Anthony, 1996; Kane, 2004). Black (2007) preferred to use a more general term to define independent learning and he claimed that the aim of 'student-centred learning' is to create "engaged and independent learners" (Black, 2007, p.6). Mok and Chen (2001) considered the term 'self-learning' and they used this term synonymously with self-regulated learning. As can be seen, although different countries' scholars have used different terminologies in order to describe students taking responsibility for their own learning and becoming more independent in their learning, there are vast similarities among the descriptions of the different terms.

2.3.3 Fundamental Components of Independent Learning

Looking at the literature, the fundamental components of independent learning can be categorised into two groups. Whilst the internal components are the set of skills which learners need to acquire; the external components are the provision of an appropriate, enabling environment and the relationship between the educator and the learner. In this section, these fundamental components of independent learning will be examined in detail.

2.3.3.1 Internal Components

The internal components are the skills that individual learners need to acquire. A review of the literature indicates that there are many skills required for independent learning to occur effectively. These skills are usually divided into three groups: cognitive skills, metacognitive skills and affective skills. Many authors have suggested that all these skills are important for learning (Birenbaum, 2002). Cognitive skills include memory, attention and problem-solving skills; metacognitive skills are skills associated with an understanding of how learning occurs, such as students being able to state how they learn and being able to identify other people who help them with their learning; and affective skills are those skills that are related to feelings and emotions, such as developing a value system, then internalising and acting on these values.

For independent learning to occur, it is necessary for learners to have some basic cognitive skills, such as memory, attention, problem-solving and creativity (Anthony, 1994; Boekaerts, 1997; Carr, 1996; Malone & Smith, 1996; Weiss, 2004; Zimmerman *et al*., 1996; Zimmerman, 1998). It is emphasised in the literature by some scholars (Boekaerts, 1997; Zimmerman, 1998) that a specific level in cognitive development is necessary for independent learning to be possible. This idea has its roots in Piaget's theory of cognitive development (Piaget, 2001). Malone and Smith (1996) also emphasised the importance of learner readiness. This means that students need to have the necessary intellectual capabilities, such as basic decoding skills, before being able to start on the process of independent learning (Carr, 1996). Malone and Smith (1996) also suggested that these intellectual capabilities develop as people get older. In contrast, Taggart *et al.* (2005) claimed that even young children have previously unsuspected strategic competence and an awareness of learning, such as being able to use strategies and set goals. It has been shown that young children can be taught to use these strategies (Bransford *et al*., 2000), indicating that cognitive skills can be taught at very early ages, and that teachers can have a direct influence on students becoming independent learners at earlier ages than those suggested in the literature. In this study, the sample was university students so age-related cognitive development was not an issue that needed to be taken into account.

In terms of the metacognitive skills required for independent learning, it has been shown by numerous researchers that these skills are developed long before higher education (Bransford *et al*., 2000; Bullock & Muschamp, 2006; Malone & Smith, 1996). Bullock and Muschamp (2006) found that year-six pupils are able to describe how they learn, stating that learning involves listening, remembering, note-taking, learning by doing, guessing, applying previously learnt knowledge and formal strategies, such as 'look, cover, write, check'. Bransford *et al.* (2000) also found that between the ages of five and ten, children are already able to talk about and reflect on learning, and this ability grows throughout the school years.

The importance of affective skills – the most significant of which is usually stated to be motivation – for independent learning is well documented in the literature (Bishop, 2006; Malone & Smith, 1996; Marcou & Philippou, 2005; Neber & Schommer-Aikins, 2002). For instance, Ommundsen (2003) concluded that students' use of self-regulatory strategies is not sufficient for them to learn: motivation is also necessary. To emphasize the importance of motivation in independent learning, numerous reasons can be considered. Students who are motivated to choose a task when given the opportunity display greater progress than unmotivated ones (Zimmerman & Kitsantas, 1999); students who are motivated to put in an increased effort to learn a difficult task display higher levels of mastery (Schunk & Hanson, 1985); students who are motivated to persist are more likely to learn on their own compared with their non-motivated peers (Schunk, 1984); and students who are highly motivated experience greater satisfaction when given the opportunity to learn than less motivated students (Zimmerman & Kitsantas, 1999).

There is a lack of agreement in the literature on whether these skills necessary for independent learning are domain-specific or whether they can be readily transferred across different subjects. There is also little agreement in the literature on whether these skills require a certain developmental stage or whether people can be taught them at any age, which is an important criterion for research studies which use samples of young children. However, particularly for higher education, there is a general agreement that students come to the tertiary level of education with a specific level of readiness to embark on the process of independent learning. Furthermore, educators can also promote this readiness for independent learning. Considering the current findings in the literature, higher education is an important platform for the recognition and the development of independent learning skills.

2.3.3.2 External Components

The most commonly mentioned external components of independent learning in the literature are the provision of an appropriate, enabling environment and the development of a strong relationship between the teachers and the students.

Whilst many authors have highlighted the importance of an enabling, supportive environment for promoting independent learning, (Alexander *et al*., 1992; Bates & Wilson, 2002; Boekaerts, 1997; Gorman, 1998; Kesten, 1987; Williams, 2003), this idea has often been introduced without the scholars identifying what the components of such an environment are (Malone & Smith, 1996; Paris & Paris, 2001; Sharp, Pocklington & Weindling, 2002). In an attempt to fill this gap, MacBeath (1993) proposed a hierarchy of environmental support which is needed for independent learning. In this model, the physical environment is the base of this hierarchy since "without this nothing is feasible" (MacBeath, 1993, p.9). The physical environment refers to the environment in which independent learning takes place, such as a library or a classroom. Following this base is the time environment, which can be used and controlled by teachers. The time environment can therefore refer to the length of time teachers give students to work on specific tasks. Then there is the peer environment, whose norms and expectations might increase or decrease students' motivation and ability to undertake independent learning. This is followed by the material resources, which refers to study materials such as books and audio tapes. Finally, at the top of the hierarchy are the tutor resources, which refer to the features, knowledge and skills of teachers, tutors and mentors. This importance of the enabling environment indicates that independent learning does not occur in isolation.

Although the provision of an appropriate, enabling environment is an essential element of independent learning, it is not sufficient. A further essential element of independent learning is the relationship between the educator and the learner, which is based on trust and a mutual responsibility for learning. Black (2007) suggested that trust and mutual responsibility are established by educators providing students with explicit messages about learning. The significance of such a relationship has been highlighted by many scholars (Alexander *et al*., 1992; Bates & Wilson, 2002; Boekaerts, 1997; Gorman, 1998; Kesten, 1987; Williams, 2003). Sharp *et al.* (2002) suggested that the new relationship between educators and learners should be based on the creation of a more informal atmosphere within lectures, which includes lecturers being highly spontaneous in responding to students' interests and needs. Their research indicates that this serves as a strong motivator for students to engage in learning and allows for more flexibility and creativity in their learning.

2.4 Innovative Instruction Strategies which Aim to Promote Independent Learning in HE

There is a consensus in the literature concerning the importance of promoting independent learning through a variety of teaching strategies (Evans, 1995). This leads educators to build up a repertoire of strategies to promote independent learning and gradually engage students in becoming more independent in their learning. Whilst the general point has already been made about the usual approach to teaching at university being traditional and mainly lecture-based which promotes the emergence of dependent learners (see Chapter 1), it is important to acknowledge here that over the last few decades there has been an extensive movement internationally to change higher education teaching through a range of innovations which aim to promote independent learning. Although such approaches may well still represent a small minority of courses, there is a body of literature discussing these approaches which is relevant to the aims of the course studied in this research study. In this section, the body of literature related to innovative teaching approaches which aim to promote independent learning will be reviewed.

2.4.1 Project-based Learning

Project-based learning is a student-driven, teacher-facilitated approach which aims to promote independent learning. Learners pursue knowledge by asking questions that have piqued their natural curiosity. The essence of a project is an inquiry. Students develop a question and are guided through research under the teacher's supervision. Student choice is a key element of this approach. Students can either work individually or if they have similar inquiries they can elect to work cooperatively in a group, thereby nurturing collaboration and communication skills as well as improving independent learning skills. Project-based learning is a key strategy for creating independent thinkers and learners (Bell, 2010). Students solve real-world problems by designing their own inquiries, planning their learning, organizing their research and implementing a multitude of learning strategies. Students flourish under this learner-centred approach to learning and gain valuable skills that will build a strong foundation for their future learning. Within this framework, students ask and refine questions, debate ideas, make decisions, design plans and/or experiments, collect data, draw conclusions, communicate their ideas and findings to others, ask new questions, and create artefacts (Blumenfeld *et a*l., 1991). Moreover, project-based learning is adaptable to different types of learners and learning situations (*ibid.*).

There is a body of literature discussing the findings related to project-based learning. Overall, the research on project-based learning reports positive outcomes related to student learning in the areas of content knowledge, collaborative skills, engagement and motivation, and critical thinking and problem-solving skills. In measuring academic subject proficiency (by using standardized testing which measures the specific content knowledge), research has shown that students engaged in project-based learning outscore their traditionally educated peers over the course of three years (Geier *et al*., 2008). Boaler (1999) prepared a study design in which students were taught using traditional mathematics programmes at one school and project-based learning at another school. Three times as many project-based learning students achieved the highest possible grade in the national exam than the students at a traditional school. Students in the project-based learning environment were equally able to answer procedural questions that used formulas, but they were superior in answering applied and conceptual problems. Similarly, Thomas (2000) showed that in a school in Boston which implemented a project-based learning programme called Expeditionary Learning, eighth graders exhibited the second highest scores in the district on a standardized test compared with their thirteenth position in a previous assessment. In terms of increase in content knowledge, as recent research studies have shown, project-based learning has several positive effects. Particularly in the higher education context, compared with traditional lectures, students in project-based learning environments performed better on assessments of content knowledge (Boaler, 1997; Penuel & Means, 2000; Stepien, Gallagher & Workman, 1993). Research also reported that project-based learning had a positive effect on specific groups of students. For example, students with average to low verbal ability and students with little previous content knowledge learned relatively more in project-based learning environments than in traditional lectures (Mergendoller, Maxwell & Bellisimo, 2006; Mioduser & Betzer, 2003). In addition, students were able to demonstrate specific content area skills after taking part in project-based learning

(Mioduser & Betzer, 2003; Peck *et al*., 1998). For instance, students working on a geometry project linked to architecture and design at university level utilized measurement skills as they developed their blueprints, of which 84% met architectural building standards (Barron *et al*., 1998). In summary, it can be claimed that usually students taught in project-based learning environments emerge with useful, real-world content knowledge which they can apply to a variety of tasks (Boaler, 1997).

However, considering the fact that this type of teaching strategy is usually preferred to achieve higher educational aims such as improving independent learning skills, the results of the studies which only focus on the content knowledge may be considered as inadequate compared with those of research studies which focus on the skills and values of the students as well as content knowledge. Numerous studies around the world have proposed project-based learning as the most suitable means of achieving effective education that integrates knowledge, skills and values (Chinnowsky *et al*., 2006; Gijselaers, 1996; Johnson, 1999; Kelly, 2007; Mulcahy, 2000; Padmanadhan & Katti, 2002; Parsons *et al*., 2005). In the literature there are important studies which have shown that students who participated in project-based learning benefited from improved critical thinking and problem-solving skills (Mergendoller *et al*., 2006; Shepherd, 1998; Tretten & Zachariou, 1995). In particular, one study of project-based learning showed a positive effect on low-ability students, who increased their use of critical-thinking skills including synthesizing, evaluating, predicting and reflecting by five times, whereas high-ability students improved only by two times (Horan *et al*., 1996). Furthermore, during project-based learning, students showed initiative by utilizing resources and revising work, behaviours that were uncharacteristic of them before they engaged in project-based learning (Barron *et al*., 1998); utilizing resources and revising work are common features of independent learners. In a recent study, students demonstrated better problem-solving skills in project-based learning than in more traditional lectures and were able to apply what they had learned to real-life situations (Finkelstein *et al*., 2010).

Project-based learning has also resulted in high levels of student engagement (Belland, Ertmer & Simons, 2006; Brush & Saye, 2008). For instance, in one study within an economics module, a project-based learning unit engaged the lowest and highest level students as well as those students who were least interested in economics at the start of the unit (Ravitz & Mergendoller, 2005). Another study reported that project-based learning had a positive effect on student motivation to learn (Bartscher *et al*., 1995). According to some teachers who reported using a third of their overall instruction time for project-based learning activities, students' work ethic improved as well as their confidence and attitudes towards learning as a result of these activities (Tretten & Zachariou, 1995). Conversely, one study found that high-school student engagement and/or participation were difficult to maintain in project-based learning (Edelson, Gordon & Pea, 1999). This result may be due to the quality of the project-based learning environment provided to the students, students' readiness for project-based learning activities or students' bad relationship with their teachers.

In addition, project-based learning has been shown to benefit a variety of students in developing collaborative skills. For example, through project-based learning, students learned to understand multiple perspectives (ChanLin, 2008) and conflict resolution skills (*ibid.*); special education students developed social skills such as patience and empathy (Belland *et al*., 2006); and low-ability students in higher education demonstrated initiative, management, teamwork and conscientiousness as they worked in groups (Horan, Lavaroni & Beldon, 1996). Students also enjoyed project-based learning because it gave them opportunities to interact with their friends and make new friends through cooperative projects (Belland *et al*., 2006; Lightner, Bober & Willi, 2007). However, group- and self-efficacy were found to depend largely on the quality of the group process since in some cases students struggled to work positively in groups (Achilles & Hoover, 1996).

On the other hand, several studies have found that project-based learning is challenging for teachers to enact despite its positive benefits. For example, one study (Marx *et al*., 1997) found the following barriers to the successful implementation of project-based learning: (a) projects were time-consuming, (b) classrooms felt disorderly, (c) teachers could not control the flow of information, (d) it was difficult to balance giving students independence and providing them with support, (e) it was difficult to incorporate technology as a cognitive tool, and (f) authentic assessments were hard to design. In addition, it was found that teachers generally focused on addressing one or two of these challenges at a time and moved back and forth between old habits and new ideas, incorporating the new information only gradually and with varied success (Marx *et al*., 1994; Marx, Blumenfeld, Krajcik & Soloway, 1997). Teachers can also struggle with entrenched beliefs when attempting to implement project-based learning. For example, it may be challenging to negotiate between giving students opportunities to explore their interests or covering the curriculum standards, allowing students to develop individual answers or providing students with one correct answer, and empowering students to regulate their learning or controlling the distribution of expert knowledge (Ladewski, Krajcik & Harvey, 1991). These issues should be taken into account in any attempt to apply project-based learning.

To sum up, research has indicated that project-based learning: (a) can have a positive effect on students' content knowledge and the development of skills such as collaboration, critical thinking, independent learning and problem solving; (b) can benefit students by increasing their motivation and engagement; and (c) may be challenging for teachers to implement. These results lead to the conclusion that teachers need support in order to plan and enact project-based learning effectively whilst students need support including help setting up and directing an initial inquiry, organizing their time to complete tasks, and integrating technology into projects in meaningful ways (Brush & Saye, 2008; Krajcik *et al*., 1998).

2.4.2 Problem-based Learning

Although new in some aspects, problem-based learning (PBL) is generally based on ideas that originated earlier and have been nurtured by different researchers (Ausubel, Novak & Hanesian, 1978; Bruner, 1959, 1961; Dewey, 1910, 1944; Piaget, 1954; Rogers, 1969). What distinguishes PBL from similar types of teaching approaches is that in PBL, the problems encountered are used as a tool to achieve the required knowledge. PBL, as it is known today, probably originated in the 1950s and 1960s. It is claimed that it grew from dissatisfaction with the common medical education practices in Canada (Barrows, 1996; Neufield & Barrows, 1974). Nowadays, PBL is developed and implemented in a wide range of domains such as education, psychology, business and science (Belt *et al*., 2002; Coombs & Elden, 2004). It is an alternative approach to teaching and learning which encourages the active involvement of the learner and promotes independent learning (Tan, 2004). As a learner-centred method that challenges the learner to take a progressively increasing responsibility for his/her own learning, PBL is therefore also consistent with the constructivist theory (Coombs & Elden, 2004). Furthermore, it also draws from another aspect of constructivism, which is to do with learning through social interaction, which recognises the impact of others' ideas on the way learners make sense of things (Harlen, 2006).

The aim of PBL is to develop independent, reflective, lifelong learners who can integrate knowledge, think critically and work collaboratively with others (MacKinnon, 1999), thus enhancing the chances of students emerging from tertiary level education with some of the skills that are highly desirable in the work place. Furthermore, by using unstructured real-life problems rather than the content as the focus, students are given opportunities to learn how to learn (Tan, 2004).

In spite of the many variations of PBL that have evolved, a basic definition is needed to which other educational methods can be compared. Six core characteristics of PBL were distinguished in the model described by Barrows (1996). The first characteristic is that learning needs to be student-centred. Second, learning has to occur in small student groups under the guidance of a tutor. The third characteristic refers to the tutor as a facilitator or guide. Fourth, authentic problems are primarily encountered in the learning sequence, before any preparation or study has occurred. Fifth, the problems encountered are used as a tool to achieve the required knowledge and the problem-solving skills necessary to eventually solve the problem. Finally, new information needs to be acquired through independent learning. Consequently, a valid assessment system can evaluate students' competencies with an instrument based on real life, such as authentic problems (Baxter & Shavelson, 1994; Birenbaum, 1996; Shavelson, Gao & Baxter, 1996). The assessment of the application of knowledge when solving problems is an essential for PBL. Therefore, usually test items require students to apply their knowledge to commonly occurring and important problem-solving situations (Segers, Dochy & De Corte, 1999), rather than measuring students' factual knowledge.

2.4.2.1 Impact of PBL on Achievement

In the literature, the results showing what students learn from PBL are mixed. Much evaluation of PBL has examined traditional academic outcome measures such as examination scores. In general, several meta-analyses have demonstrated that PBL students scored slightly lower than students under traditional settings on multiple-choice measures of academic achievement such as the National Board of Medical Examiners (NBME), which examines basic science knowledge (Albanese & Mitchell, 1993; Goodman *et al*., 1991; Mennin *et al*., 1993; Vernon & Blake, 1993). However, meta-analyses also showed that PBL students performed slightly better than traditional students at tasks related to problem solving such as NBME II and on ratings and tests of clinical performance (Albanese & Mitchell, 1993; Vernon & Blake, 1993). These results imply that whilst PBL students show slightly lower abilities to present their science knowledge in traditional exams, they do better at examinations which require them to apply their knowledge into different contexts. In a more recent meta-analysis, Dochy *et al.* (2003) found that there was no effect of PBL on measures of factual knowledge, however studies of knowledge application have demonstrated a moderate effect size favouring PBL students compared with traditional students. Although multiple-choice tests measure knowledge, they may not get at the type of extensive and flexible knowledge aligned with the goals of PBL. More complex measures of flexible knowledge application may be more sensitive to the effects of PBL. Other studies have examined how PBL students performed on a problem-solving task (Hmelo, 1998; Hmelo *et al*., 1997; Patel, Groen & Norman, 1991, 1993). Patel *et al.* (1991, 1993) asked traditional and PBL students to provide diagnostic explanations of everyday problems. The PBL students' explanations, although more error-prone, were also more elaborated than those of the students in traditional curricula. This result is consistent with research that has demonstrated that when people are first attempting to apply new knowledge, they do not always do it well (Lesgold *et al.*, 1988; Novick & Hmelo, 1994). Chi *et al.* (1994) suggested that errors are a necessary step in learning to apply new knowledge. By articulating incorrect knowledge, learners have the opportunity to revise their false beliefs when they are confronted with correct knowledge. In an innovative engineering course in sustainable technology, students used PBL in multidisciplinary teams (Hmelo *et al*., 1995). They were given pre-tests and post-tests assessing both factual knowledge and problem-solving skills. The students demonstrated increases on both measures. When PBL was used to teach statistical reasoning to undergraduates, Derry *et al.* (2000) demonstrated that students showed learning gains for some, but not all, of the course content using a pre/post design. In a course for pre-service teachers using video problems and a web-based information resource, Derry *et al.* (2006) found evidence that their PBL approach led to the transfer and flexible use of course concepts. Moreover, Schwartz and Bransford (1998) conducted a controlled study of students on an undergraduate psychology course. They compared students in three groups: (a) students who just solved problems, (b) students who read a textbook chapter prior to attending a lecture, and (c) students who solved problems prior to attending a lecture. They found that students who solved problems prior to the lecture performed better on a problem-solving task than students who read the chapter or those who just solved problems. This finding suggests that attempting to solve a problem helps create a readiness to learn from a lecture. The results from these studies of undergraduate students provide additional evidence that problem-based curricula can help students to construct knowledge which they can then apply into different contexts. From the literature, PBL appears to support learning particularly in undergraduate and professional educational contexts.

2.4.2.2 Impact of PBL on Independent Learning

One of the proposed benefits of PBL is its claim to prepare lifelong learners because of its emphasis on independent learning. When students in PBL curricula in three different disciplines were interviewed, Dahlgren and Dahlgren (2002) found that students in two of three disciplines felt a great sense of uncertainty about what to study at the beginning of their courses. However in PBL settings, students' independent learning strategies evolve over time (Evensen, Salisbury-Glennon & Glenn, 2001). Developing independent learning skills is a difficult and multifaceted process for students and the question of whether PBL actually helps them to develop independent learning skills has been investigated by quite a few scholars (for instance, Hmelo-Silver, 2004). One way to study this is, as was done by Hmelo-Silver (2004), by examining component processes in independent learning such as how students generated learning issues, planned their learning, and integrated new knowledge in problem solving. Hmelo and Lin (2000) examined these component processes by comparing students in traditional and PBL curricula who had completed a pathophysiological explanation task. They found that the PBL students transferred the hypothesis-driven strategies from their problem solving into their independent learning as they used their hypotheses to plan their learning. Moreover, they were more likely to integrate new information into a revised explanation than traditional students. In a study comparing traditional and PBL university students in terms of the learning resources they used, Blumberg and Michael (1992) found that PBL students were more likely to use self-chosen learning resources whereas students in the traditional lecture-based instruction used faculty-chosen resources. PBL students were more likely to report selecting the material to study themselves, whereas conventional curriculum students reported reading specific teacher-generated assignments. Engineering students on a PBL course in sustainable technology increased their use of expertise beyond that provided by course instructors as the course progressed and tended to use a variety of student-selected resources throughout the course (Shikano & Hmelo, 1996).

One indicator of effective problem-solving skills is the ability to transfer reasoning strategies to new problems. Patel *et al.* (1991, 1993) asked traditional and PBL students to provide diagnostic explanations of an everyday-life-related problem. They showed that students in the PBL curriculum were more likely to use hypothesis-driven reasoning (as they were taught) than were students in a traditional curriculum. The students in the traditional lecturing environment predominantly used data-driven reasoning, a form of reasoning that is more characteristic of experts, but only on familiar problems (Norman *et al*., 1994). In two studies, students in PBL curricula transferred the hypothesis-driven reasoning strategy to unrelated problems and generated more coherent explanations than students without PBL experience (Hmelo, 1998; Hmelo *et al*., 1997). When comparing students who were traditionally instructed with students in a PBL class on problem-solving skills, Gallagher, Stepien and Rosenthal (1992) found that PBL students were more likely to include problem finding (which is an essential aspect of problem-solving skills particularly for ill-defined problems) as a step when presented with a novel ill-structured problem. Although research on the influence of PBL on students' skills development is limited compared with research on the influence of PBL on students' learning, it does provide some evidence that students in PBL learn problem-solving, reasoning strategies and independent learning skills that may be transferable to new problems.

2.4.3 Promoting Independent Learning through ICT

There is an implicit assumption in the literature related to independent learning that information and communications technology (ICT) is an essential component of the enabling environment which is necessary to promote independent learning. All components of an enabling environment, physical environment, time environment and peer environment are supported with ICT. The physical environment in universities is being increasingly equipped with many forms of ICT, such as the internet, electronic whiteboards, computers with various software, and mobile devices. Similarly, the time environment and the peer environment are likely to be influenced by ICT since lecturers and students are able to communicate by various means, including electronically and physically. This may provide more flexibility in the time that students have for learning content and learning about learning. The material resources are primarily based on ICT, with students more likely to use an internet library than a physical library when searching for information. The tutor resources are also likely to be influenced heavily by ICT since lecturers' knowledge and skills are enhanced and developed through ICT.

The part that ICT has to play in learning is widespread throughout the independent learning literature although its role in relation to independent learning is implicit (Hinds, 2007; Malone & Smith, 1996; Wilson, 2000). There is a comprehensive body of literature documenting the importance of ICT for independent learning (Mok & Chen, 2001; Lim & Chai, 2004; Peet, 2000; Stefansson, 2004). Most of this literature focuses on work carried out in East Asia and North America and may not be directly applicable to the context in which this current study was undertaken. However, since the principal elements of independent learning remain identical across countries, this literature may lead the way to a better understanding of how ICT can support and promote independent learning in the UK context. Summing up the various benefits of ICT proposed in the literature, Mok and Chen (2001) proposed four ways in which independent learning is facilitated:

- ICT allows for the easy assessment and measurement of independent learning;
- ICT has dramatically increased the speed and access of information;

- ICT allows for more in-depth feedback, such as through the use of multimedia; and
- ICT breaks down the barrier between the learner and the educator, and allows learners to interact easily with each other.

In contrast, the possibilities of ICT bring with them a number of challenges. Developing materials requires a major input of time, effort and expertise from teachers, the more so with emerging digital technologies (Wagener, 2006). Page (1989) stressed the importance of students being actively and creatively engaged in the production of ICT resources for learning. Page noted that this is possible if, for example, lecturers encourage students to produce videos and computer programmes, and to make slide presentations. This indicates that engaging students in the production of ICT materials might ensure that the ICT materials used for independent learning are relevant and appropriate.

2.4.4 Moving In-Class Modules Online

For almost two decades, institutions of higher education have been exploring ways to improve teaching and learning practices through creative and innovative uses of internet technology (Laurillard, 2013). By and large, reasons for past and present explorations stem from a persistent belief that internet information and communication tools are effective at removing geographical and situational learning barriers, provide opportunities for increased interaction between and among instructors and learners, and can increase the quality of learning experiences (Bates, 1995; Garrison & Anderson, 2003; McGreal, 1998). Additional reasons for moving in-class modules online include institutional pressures such as supposedly it helps to save money for institutions, or technological factors such as demands from students for high-tech experiences that might be experienced elsewhere (Seery, 2012).

However, Salmon (2002) proposed that before considering a move online, educators should ask themselves what the pedagogic rationale is for considering such a move rather than thinking about the practical considerations. Pedagogic reasons for change may include attempts to enhance student-centred activity, to harness technology to provide rapid feedback, to facilitate student group work, to provide student support to large groups and/or to develop intimacy in the student-teacher relationship with large groups (Salmon, 2002). These institutional pressures or practical reasons are not likely to motivate educators to create sound online learning environments. This concern is supported by the findings of recent reports. Most lecturers and students would consider the virtual learning environment (VLE) as the centre of where e-learning is situated. However, the evidence to date is that such dedicated spaces are mainly used as content repositories for notes, additional links to journal articles and supplementary material, rather than being the centre of online learning. A survey of several Irish higher education institutions in the Dublin region, representing 76, 000 students and 4500 staff, found that in the majority of cases, VLEs were being used as repositories rather than learning environments, with most courses having anything from about half to all coursework incorporated into the VLE. Microsoft Word, Microsoft PowerPoint and PDF files were the most common formats, with 75% of students surveyed reporting that they accessed the VLE to get copies of lecture notes and just over 60% accessing to get other course material (DRHEA, 2009). This situation is no different in the UK; in a review of the student learning experience in chemistry by the Higher Education Academy Physical Sciences Centre in the UK, students ranked 'e-learning' as both the least effective and the least enjoyable from a range of teaching options (Gagan, 2008). There can be a variety of reasons behind the failure of VLE being used as effective learning environments such as academic staffs' lack of knowledge and interest in promoting online learning or their concern over increased workload. However, lecturers' lack of pedagogic rationale before they take the action to move in-class modules online is probably the most worrying one.

On the other hand, if applied appropriately with a pedagogic rationale, moving in-class modules online can have a variety of positive impacts on students' learning experience. There is evidence that positive perceptions about online modules are growing as internet technology becomes more pervasive and transparent. For example, a survey conducted by McGraw-Hill Ryerson and referred to by Saundercook and Cooper (2003) was completed by 1177 Canadian and 975 American faculty members, and revealed that 57% of the survey participants believed that online courses have a positive impact on content, course delivery and student learning. This percentage was up from 22% in 1999. The survey participants further expressed the view that the use of internet technology is effective at achieving greater student participation and greater student interest (Saundercook &

Cooper, 2003). The findings on higher levels of learning attract particular interest, for instance the same study revealed faculty members' perception that “web-based technology allows the opportunity to … improve critical thinking” (Saundercook & Cooper, 2003, pp.17-18).

In addition, the related literature has suggested that moving in-class modules online can transform learning experiences in positive ways, increasing the quality of the learning experiences with respect to the development of higher order thinking skills (Garrison & Anderson, 2003; Heckman & Annabi, 2005; McKnight, 2001). Similar to these findings, it was found that text-based internet communication tools which are the essence of online modules facilitate the development of argument formation capabilities, increased written communication skills, greater complex problem solving abilities, and increased opportunities for reflective deliberation (Abrami & Bures, 1996; Garrison, Anderson & Archer, 2001; Hawkes, 2001; Winkelmann, 1995). The fundamental assumption which supports these findings is that asynchronous text-based internet communications such as discussion boards can facilitate higher levels of learning, for instance, critical and creative thinking skills. Lapadat (2002) claimed that these findings are due to the fact that learners have the means to carefully compose their ideas into a written form of communication in asynchronous text-based internet tools. Similarly, it has been claimed (Garrison & Anderson, 2003) that the success of asynchronous communication is because it provides learners with opportunities for critical reflection which is necessary for higher ordered learning goals such as critical and creative thinking.

In an effort to legitimize these claims, research has been conducted on the effectiveness of learning in the online classroom. However, there is as yet no consistent and reliable body of knowledge indicating that higher levels of learning are an outcome of the use of internet technology – nor many details as to what works, why, in what ways, and under what conditions (Naidu, Cunnington & Jansen, 2002). Perhaps the only consistent finding is that deep and meaningful learning is not easily achieved in the online classroom (for instance, Garrison *et al*., 2001; Gunawardena, Lowe & Anderson, 1997; Kanuka & Anderson, 1998). Even if it is shown that internet technology can bring about higher levels of learning (Klemm & Snell, 1996), much remains to be understood about implementing online learning activities to facilitate the development of a meaningful educational experience (Kanuka & Garrison, 2004).

2.4.5 Flipped Classrooms

One of the other significant attempts to personalise instruction, which generally includes identifying the needs and capabilities of individual learners, making instruction relevant and meaningful, and providing flexibility in scheduling, assignments and pacing (Keefe, 2007), is flipping classrooms. The goal of personalising instruction usually means replacing traditional models of education with more customized instruction strategies. As has been said earlier, traditional classrooms cannot always provide this type of differentiation, which has led some educators to recommend using the flipped classroom approach blended with other approaches in learning environments instead of using the flipped classroom approach as the only teaching approach (Cornelius & Gordon 2008; Dziuban 2004; Garrison & Kanuka 2004; Patterson 2012; Verkroost *et al*., 2008) which incorporates technology in an effort to flip the classroom (Bergmann, Overmyer & Wilie 2012; Friedman & Friedman 2001). The idea of flipping the classroom is not new (Pardo *et al*., 2012), but it has recently gained prominence due to advances in technology and increased ubiquitous access to computers and other mobile devices (Davies & West 2013).

Many educators are promoting the use of both technology and some version of an inverted classroom often in a blended learning environment (Alvarez 2011; Berrett 2011; Dziuban 2004; Fulton 2012; Graham 2006; Hughes 2012; Khan 2012; Kleiman 2000; Novak 2011; Talbert 2012). However, much of the research regarding the specific pedagogical approach to flipping the classroom has recently started to be published and is often based on contextually situated learning circumstances (Lage, Platt & Treglia, 2000; Moravec, Williams, Aguilar-Roca & O'Dowd, 2010; Strayer, 2007, 2012).

A simple description of flipping the classroom is to replace after-lecture homework with the expectation that students study course material prior to class (Alvarez 2011; Moravec *et al*., 2010). Class time is then dedicated to practice assignments, targeted remedial help, or activities designed to promote higher order thinking skills (Khan, 2012). Whilst many online resources are being developed (*see*, for example, Carnegie or Cengage Learning), one of the most prominent examples of online resources for flipping the classroom is the Khan Academy, a funded project that provides open educational video resources on a variety of subjects (*see* http://www.khanacademy.org/). The idea of flipping the classroom with resources such as the Khan Academy is not very sophisticated (Khan, 2012). Rather than the teacher providing synchronous in-class group instruction, students are expected to use the video resources provided, along with other materials, to learn concepts and complete tasks on their own at their own pace and at locations convenient to them. Individual students can focus their efforts on their individual learning needs so that they are not left behind by class discussions that go too fast, or become bored by class time which is spent covering content which they already know. Effective flipped classrooms share a few important characteristics which are also common to other reviewed instruction strategies that promote independent learning: (1) students transform from passive listeners to active learners, (2) technology often facilitates the students' attempts, (3) class time and traditional homework time are exchanged so that homework is done first and class time takes on a more flexible environment to help personalize instruction, (4) content is given context as it relates to real-world scenarios, and (5) class time is used either to help students to grasp especially challenging concepts or to help students engage in higher orders of critical thinking and problem solving (Bergmann, Overmyer & Wilie, 2012). Just like the previously reviewed teaching approaches, flipping the classroom assumes that students will become independent learners through taking control of their learning in terms of the pace of study, mastery of content and responsibility for coming to class prepared (Alvarez, 2011; Fulton, 2012). It was found in the literature that if applied appropriately, the flipped classroom was both effective and scalable, particularly for undergraduate students; it better facilitated learning than the simulation-based training and students found this approach to be more motivating in that it allowed for greater personalisation of instruction (Davies, Dean & Ball, 2013).

2.5 Promoting Independent Learning

The literature reviewed above clearly indicates that students do not become effective independent learners by themselves. Rather, they need to learn how to learn, indicating that effective ways to learn can and should be promoted by educators (Artelt, Baumert, Julius-McElvany & Peschar, 2003; Gorman, 1998; Paris

& Paris, 2001; Van Grinsven & Tillema, 2006). The promotion of independent learning requires a new role for teachers which is based not on the traditional transmission of information, but on student-centred teaching, which ensures that students are actively involved in the learning process. The literature provides a variety of suggestions relating to how teachers can promote independent learning by using a range of strategies, including scaffolding (Black, 2007; Gorman, 1998; Vygotsky, 1978); providing students with opportunities to self-monitor (Ley & Young, 2001; Paris & Winograd, 1990); offering models of behaviour (Bolhuis & Voeten, 2001; Corno, 1992; Montalvo & Torres, 2004); developing a language for learning (Allan & Lewis, 2001) and providing feedback on homework (Allan & Lewis, 2001).

Scaffolding is based on Vygotsky's (1978) idea that cognitive development is based on children following the example of a more capable other. Scaffolding can involve teachers initially guiding students in their practice, the objective during this practice being the gradual transfer of responsibility from the lecturer to the student. It is important that taking away this scaffold is accomplished step by step, moving from more directive instruction in the initial stages to increased independence (Bolhuis & Voeten, 2001; Montalvo & Torres, 2004). Black (2007) noted that the scaffolding model takes into account that students differ in their existing knowledge and skill, and that their learning progresses at differing rates. The notion of scaffolding supports the view that people learn by making links with what they have previously learnt. Similar ideas have also been highlighted by other scholars (*see* Taber, 2011). Wallace (2002) suggested that lecturers can use brainstorming to determine what students already know and encourage them to access their previous knowledge. Also, Wallace suggested that mind-maps can be drawn to encourage students to link new information to what they already know. Myhill and Warren (2005) suggested that teachers can gradually remove the supportive scaffold by responding flexibly to students' responses rather than following a predetermined teaching path. This is highly motivating for students; it leads to increased levels of student participation and gradually moves them towards more independence in their learning.

Other scholars have suggested that independent learning can be promoted by allowing students to model the behaviour of their teachers (Bolhuis & Voeten, 2001; Corno, 1992). With time, this allows students to solve problems similar to the ones they previously observed others doing. It is therefore proposed that modelling might allow students to assimilate the steps taken in planning, controlling execution, distributing cognitive resources and reflecting on what has been done (Montalvo & Torres, 2004). Montalvo and Torres (2004) also proposed that in addition to observing teachers, students could also be encouraged to observe other expert models, such as more experienced peers.

Others have proposed that teachers should provide students with opportunities to self-monitor to promote independent learning since this process is a key element of self-regulation (Ley & Young, 2001). They defend the idea that educators should provide students with continuous evaluating information and give them the chance to self-evaluate.

A further important aspect related to how teachers can promote independent learning is the provision of relevant and appropriate homework. Allan and Lewis (2001) suggested that homework supports students' learning if it is relevant, rational and based on tasks that they can relate to during their everyday lives.

Allan and Lewis (2001) also stressed the development of a language of learning. The purpose behind the development of this language of learning is to help students to become more aware of their learning styles and to foster communication between students and lecturers. Importantly, this verbalisation may also ensure that students attribute improved performance on a task to the use of effective strategies, an importance that has also been pointed out by Paris and Paris (2001).

2.5.1 The Role of the Lectures in Promoting Independent Learning

There is a variety of metaphors used for the role of lecturers in facilitating independent learning. The most common metaphors consider lecturers as coaches (Allan *et al*., 1996; Van Grinsven & Tillema, 2006), mentors (Malone & Smith, 1996) and guides (Bishop, 2006). These metaphors focus on lecturers understanding how students think and learn and then guiding them towards independence in their learning. Malone and Smith (1996) emphasised that it is important for lecturers to consider individual students rather than the class as a whole. The role of lecturers as mentors involves them relaying their enthusiasm about a topic to students and encouraging students to make enquiries for themselves. Therefore, lecturers should provide opportunities for students to make these enquiries, for example by encouraging students to ask challenging questions (Malone & Smith, 1996). This can increase students' desire to be coached or guided.

Given the importance of motivation for independent learning, several scholars have stressed the importance of lecturers motivating their students (Birenbaum, 2002; Corno, 1992; Malone & Smith, 1996; Van Grinsven & Tillema, 2006). According to Malone and Smith (1996), motivation is based on students developing interest and involvement. Lecturers can foster motivation by ensuring that success is recognised and praised. It is important for lecturers to allow all students to be successful at times, by making sure that some tasks are easy. Malone and Smith (1996) also suggested that lecturers should foster motivation by sharing the purpose of lessons with students and stating the long-term goals. It may also be possible to increase students' motivation by ensuring that the tasks provided during independent learning are based on realistic scenarios which students can relate to in their everyday lives (Marx *et al*., 1997).

2.6 Misunderstandings of Investigated Ideas in Chemistry Education

As was stated in the Introduction, one aim of this research study is to probe the impact of an instruction strategy which aims to promote independent learning on students' understanding of some chemical ideas. Hence, it is necessary to review the literature related to the students' understanding of ideas investigated in the research and covered in the Macromolecules course as well as the literature on similar instruction strategies. In previous sections of this chapter, the literature on instruction strategies which aim to promote independent learning was reviewed, and this section will now give a brief introduction to the previous research on students' understanding and will discuss the findings reported in the literature about the ideas investigated in this research study. This section has significance particularly to setting the background for detecting students' possible misunderstandings about the investigated chemical ideas.

Students' lack of in-depth understanding of science subjects has been reported repeatedly by national and international assessment bodies in the past (International Association for the Evaluation of Educational Achievement 1988; LaPointe, Mead & Philips, 1989; National Assessment of Educational Progress, 1978; 1988). Furthermore, more recent reports have demonstrated that despite an unprecedented increase in the field of science education research in the last three decades, and that some significant improvement especially in the way that we teach science has been achieved through innovative teaching approaches (as also demonstrated in previous sections of the literature review), there is still a long way to go in order to enable students to reach in-depth understanding of science subjects (Batterham, 2000; Millar, Leach & Osborne, 2000).

Particularly after the emergence of the constructivist view of learning, research on students' and teachers' conceptions and their roles in learning and teaching science has gathered significant attention from scholars in every science domain. There is common agreement among scholars in the science education domain that 'conceptual' understanding should be the core of science education. Two points become very clear after a brief review of the last four decades' literature. First, students do not come into science instruction with no previous knowledge (or belief) about the ideas that they will be taught. Second, students can gain understanding of science by relating what they have just acquired to what they already knew (or believed), which requires active work on the part of students.

It is claimed in the literature that students often develop ideas that are different from those accepted by the scientific community and intended by their facilitators (BouJaoude, 1992; Ebenezer & Fraser, 2001; Peterson & Treagust, 1989; Taber, 1999; Treagust, 1988; Zoller, 1990). These ideas have been given various names, such as alternative frameworks, misconceptions, misunderstandings or alternative conceptions (Gabel & Bunce, 1994; Griffiths, 1994; Nakleh, 1992). Even though each description has a slight difference, such as that usually misunderstandings are claimed to be less firmly rooted and so are more amenable to change compared with alternative conceptions (Griffiths, Thomey, Cooke & Normore, 1988), in essence they all refer to students' ideas which differ from the scientifically accepted ones. The reason behind the choice of the term 'misunderstanding' for this current study was explained in Chapter 1 (*see* Section 1.3.2). The main focus of this study is not to investigate deeply-rooted misunderstandings of students in chemistry education, but to see the impact of the designed teaching approach on students' understanding of some ideas from the content of the course. It is established in the literature that the detection and remediation of misunderstandings is often expected to occur over a long period of time (Niaz, 2001). The intervention time of the course was one term (approximately three months), so, maybe, it would not be realistic to expect to see changes in the deeply-rooted misunderstandings of students. As the research suggests, conceptions are highly resistant to change, and changes take a long time (Niaz, 2001).

The literature is replete with research studies which show that traditional lecturing does not lead students to a satisfactory level of understanding of scientific ideas. As described earlier in this chapter as well as the Introduction chapter, traditional lecturing is a teaching approach that usually makes students listeners and teachers presenters. In this approach, any kind of interaction (student-student and/or student-teacher) is highly limited and student engagement is not more than occasional one-way answers by students to questions. Students who are taught in this way usually end up having basic understanding at knowledge level, often simply just memorizing the facts, without any particular understanding of ideas in science. There have been numerous attempts to change the traditional teaching approaches with evolved ones including reviewed teaching approaches which aim to promote independent learning. The Macromolecules course is one of those attempts in higher education. It is important to see the impact of this new teaching strategy on students' understanding in order to make healthy conclusions about the teaching approach and its possible further application or improvement. Next in this section, the literature on students' ideas investigated in this research study will be reviewed. The ideas of students which are investigated can be categorised into four groups: students' ideas about recycling, students' ideas about intermolecular bonding, students' ideas about combustion reactions, and students' ideas about structure-property relations.

2.6.1 Students' ideas about recycling

There has been comparatively little research in the science education literature that has investigated students' ideas about recycling. However, the majority of the studies probing students' ideas about global warming offer some findings about students’ ideas about recycling. These studies show that although students usually have interactions with the ideas of recycling and reuse, their understanding of them is quite limited (Daniel, Stanisstreet & Boyes, 2004; Kılınç, Stanisstreet & Boyes, 2008; Membiela, 1993). However, all of those studies present student misunderstandings of the recycling idea in a global warming context. For instance, students usually think that individual actions such as recycling play a less significant part in global warming than industrial actions, whereas the reality is precisely the opposite. Studies on the idea of recycling are, on the contrary, far more rare. This is quite surprising, especially considering that possible negative attitudes towards recycling and reuse may stem from students’ misunderstandings and the vital environmental effects of these negative attitudes. Kortland (1992), in his qualitative analysis of student interviews, showed that the students' perception of recycling waste was limited to the pollution of air, water and soil. Depletion of raw materials was never or rarely mentioned by the students. Pollution was valued negatively by students as it was considered a possible threat to human health. Recycling was rarely or never seen as a threat to utility functions.

The review of the literature presents students’ misunderstandings about recycling and reuse as:

- Some students have understanding problems with renewable and non-renewable raw materials. Some think that recyclability is a criterion for renewability;
- Some students have understanding problems with the distinction between reusing and recycling;
- Some students have understanding problems about the limitations of recycling.

It can be inferred from these conclusions that students do have an understanding of recycling and reuse concepts, but on some issues it is still incomplete or misleading and should be treated through effective science education. Moreover, those misunderstandings possibly influence the quality of students’ related decisions in a negative way and have a huge impact on environmental issues. The detection and the treatment of students’ misunderstandings have vital significance for both science education and the future of the environment.

2.6.2 Students' ideas about intermolecular bonding

Chemical bonding is a popular topic of research among science education scholars who are interested in students' understanding of chemical ideas. One possible reason for this is that chemical bonding is very much related to the concepts of electrons, ionization energy, electronegativity, geometry, molecular structure and stability which are central for much of chemistry. Students' ideas about covalent, ionic and intermolecular bonding have been investigated by numerous researchers (Barker, 1994; Barker & Millar, 2000; Boo, 1998; Ozmen, 2004; Petersen, Treagust & Garnett, 1989; Petersen & Treagust, 1989; Taber, 1994). In the majority of those research studies, the research sample comprised secondary-school children. Furthermore, the findings of different age groups such as undergraduate chemistry students (Petersen, 1993) showed great similarities with the findings of secondary-school children's ideas about chemical bonding.

The findings of the studies show that students are confused about covalent and ionic bonds (Butts & Smith, 1987), they hold misconceptions regarding unequal sharing and the position of electrons (Petersen *et al*., 1989), they think that intermolecular bonds are stronger than intramolecular bonds (Petersen *et al*., 1989) and they think that chemical bonds are physical entities (Boo, 1998). In addition, different studies have shown a variety of students' misunderstandings, including 'chemical bonds form in order to produce filled shells rather than filled shells being the consequence of the formation of many covalent bonds', 'there are only two kinds of bonds: covalent bonds and ionic bonds. Anything else is just a force, not a proper bond', 'atoms need filled shells' and 'a covalent bond holds atoms together because the bond is sharing electrons'.

Particularly for intermolecular forces, students' most common misunderstandings from the literature included

- Intermolecular forces are stronger than intramolecular forces;
- Intermolecular forces are the forces within a molecule;
- Strong intermolecular forces exist in a continuous covalent solid;
- Covalent bonds are broken when a substance changes shape;
- Intermolecular forces are influenced by gravity;
- Molecular iodine contains 1 minus ions.

Intermolecular bonding and bonding in general are key ideas for chemistry as the lack of understanding of them can have a detrimental impact on the understanding of many other ideas such as the chemical and physical features of chemicals or chemical structures. For polymer chemistry particularly, a good understanding of intermolecular bonding is vital in order to have a grasp of polymers' structures, chemical and physical features and possible reactions.

2.6.3 Students' ideas about combustion reactions

In the literature, there have been some attempts to synthesize the findings of research studies about students' explanations of combustion. The majority of them have tried to apply general criteria to categorize the responses of students to a variety of questions (Andersson, 1986; Andersson, 1990; Barker & Millar, 1999; Meheut, Saltiel & Tiberghien, 1985; Prieto, Watson & Dillon, 1992; Watson, Prieto & Dillon 1995; 1997). In those studies, students' ideas have been classified in different ways to fit collected data from students. Watson *et al.* (1997) identified three categories, modification, transmutation and chemical reaction. Of these three groups, chemical reaction is the group that included students' scientifically correct explanations, whereas the other two categories included answers that showed some sign of misunderstanding. Some examples of the students' explanations of combustion are categorised below.

Chemical reaction thinkers;

Students recognize that the combustible substance and oxygen/air interact, but they think that the reaction is irreversible, that the flame/fire is evidence of a chemical reaction, that the product contains the reactants in a different chemical combination, and that mass is conserved.

Transmutation thinkers;

Students think that there is no interaction between the combustible substance and the oxygen/air, that burning is a destructive process, that the flame/fire is an active agent of change, that matter may be transmuted into heat and *vice versa* and that oxygen may be needed but does not interact in a chemical sense.

Modification thinkers;

Students think that oxygen/air is not involved in the change, that the change is reversible and that mass decreases.

The studies referred to above show that the majority of students do understand up to a point combustion reaction, but that there are still considerable numbers of students who have some kind of misunderstanding about combustion reactions. It has been suggested that students' thinking can be improved by context-based chemistry teaching approaches (Barker & Millar, 2000). The impact of the Macromolecules course on students' ideas about combustion reactions will be investigated in this current study.

2.6.4 Students' ideas about structure-property relationships

There are a few established misunderstandings of students about structure-property relationships in general. The most common misunderstanding can be considered as the fact that they mix up terms from the macroscopic area of matter, such as colour, density, melting or boiling point and solubility, with the sub-microscopic area of the smallest particles, such as size or mass of particles (Barke, Hazari & Yitbarek, 2009). Diamond and graphite may be given as an example to clarify this misunderstanding. Two modifications are established from the same C atoms; the chemical structures of diamond and graphite, and therefore their characteristics, are completely different. Since there is no doubt that graphite and diamond are two different substances with different chemical and physical properties and that they are both composed of carbon particles, it is not sensible to think that carbon particles can be both black and colourless or that carbon can have two different densities at the same time. Hence, learners must stop transferring the material characteristics to substances' particles.

One possible reason behind misunderstandings related to students' transfer of material characteristics to substances' particles may be the way that students have been first introduced to particles. It is a common practice for some traditional teachers to associate colours with specific particles, such as blue with oxygen atoms, green with chlorine atoms, yellow with sulphur atoms and black with carbon atoms.

Those associated colours may lead to students having misunderstandings like the one described above (Barke *et al*., 2009).

More broadly, the struggle which students have to comprehend and use the transition between macroscopic and microscopic levels has been discussed by numerous researchers (Gabel, 1994, 1998; Harrison & Treagust, 2000; Hodson, 1990; Nelson, 2002). The reasons for this may vary, such as lack of experience with the macro level or the existence of misunderstandings about the particulate nature of matter that can impede understanding of the nature of the sub-microscopic level. Chemistry is a complex structured science that works in three levels; macroscopic, sub-microscopic and symbolic. The lack of comprehension of any of those levels or of the transition between them may lead to misunderstandings similar to those discussed above.

2.7 Intellectual Attributes

Considering the fact that the investigated teaching approach's learning objectives (*see* section 3.2.4) includes improvement in some of the intellectual attributes of students, the impact of the instruction strategy which aims to promote independent learning on students' intellectual attributes is also measured. Hence, it is necessary to review the literature related to the students' intellectual attributes which the Macromolecules course intends to improve. In previous sections of this chapter, the literature on instruction strategies which aim to promote independent learning was reviewed, and this section will now give a brief introduction to the research on students' intellectual attributes and will discuss the findings reported in the literature about the impact of independent learning on those attributes. This section has significance particularly for defining those attributes and for setting the background in approaches to measuring them in science education.

In recent years there has been a tendency in educational rhetoric and policy-making in many countries to identify sets of generic intellectual attributes which it is hoped the well-educated person will possess as s/he emerges from the system. Scientific reasoning, creative thinking and self-assessment are often listed as three of these attributes, and these are also associated with independent learning. Science educators have also been interested in learners' intellectual attributes, particularly in science contexts (for example, Aikenhead, 1989; DeBoer, 1991; Eisenhart, Finkel & Marion, 1996; Glaser, 1984; Miller, 1983; Norris, 1995, 1997; Posner, Strike, Hewson & Gertzog, 1982; Ryan & Aikenhead, 1992; Schauble & Glaser, 1990, Zimmerman, 2000).

Kuhn, Amsel and O'Loughlin (1988) claimed that intellectual attributes are not values which did not exist previously and appear suddenly, but are more of a continuum; and they can be improved. Barnes (2005) argued that we find ourselves living in a time when learners are surrounded by information on the world wide web and other electronic media, but have limited abilities to decipher, question, validate and reason the substantiality or validity of the information accessed. So today, teaching approaches that have the potential to improve the intellectual attributes mentioned above have particular importance. The impact of the teaching approach applied in the Macromolecules course on students' intellectual attributes has also been investigated in this current research study, so the literature related to these intellectual attributes has required attention. The following paragraphs will now give a brief introduction to the research on intellectual attributes and will discuss the findings reported in the literature.

2.7.1 Scientific Reasoning

Scientific investigation, when it is broadly defined, includes numerous procedural and conceptual activities such as asking questions, hypothesizing, designing experiments, using apparatus, observing, measuring, predicting, recording and interpreting data, evaluating evidence, performing statistical calculations, making inferences, and formulating theories or models (Keys, 1994; Schauble, Glaser, Duschl & Schulze 1995; Slowiaczek, Klayman, Sherman & Skov, 1992). Because of its complex nature, scholars who have been interested in scientific reasoning usually have limited the scope of their investigations by focusing on either the conceptual or the procedural aspects of the topic (Zimmerman, 2000). The main focus of the procedural approach has been on domain-general reasoning and the problem-solving strategies that are involved in the discovery and modification of theories about categorical or causal relationships (for example, diSessa, 1993; Pauen, 1996; Spelke, Phillips & Woodward, 1995). The main focus of the conceptual approach has been on determining the naive mental models or domain-specific theories that learners hold about scientific phenomena and the progression of changes that these models undergo with experience or instruction (Voss, Riley & Carretero, 1995; Kuhn *et al*., 1988). In addition to these, an integrated model of the cognitive processes involved in scientific activity was suggested by Klahr and Dunbar (1988).

Although psychologists' approach to scientific reasoning is quite complex, most people think of scientific reasoning as the kind of reasoning that scientists use in the process of making new scientific discoveries (Giere, 1979). In this current study, a model suggested by Giere (1979) is used to describe scientific reasoning. He suggested a model with four components for scientific reasoning: 1) a real-world object or process under investigation; 2) a model of the real-world object or process; 3) some predictions, derived from the model, describing what the data should be like if the model fits the real world; and 4) some data generated through the sorts of interactions with the real world assumed in the predictions derived from the model. Hence, any positive impact on students' ability to model, predict and collect data to compare with predictions might be considered as a positive impact on students' scientific reasoning.

In terms of the effects of particular instruction strategies on students' scientific reasoning, there appear to be relatively fewer studies compared with the studies which focus on the instruction strategies' impact on students' understanding. Despite this, there are still quite a few studies which have documented that independent learning activities can promote scientific reasoning abilities (Adey & Shayer, 1990; Lawson, 1995; Marek & Cavallo, 1997). Adey and Shayer (1990) demonstrated that an increase of scientific reasoning ability was possible among middle- and high-school students through long-term, independent learning interventions. When an independent learning approach was used to teach scientific reasoning to undergraduates, Derry, Siegel and Stampen (2000) demonstrated that students showed learning gains for some, but not all, of the course content. Similarly, Patel *et al.* (1991, 1993) asked traditional and independent learning students to provide diagnostic explanations of a clinical problem. They showed that students in the independent learning curriculum were more likely to use hypothesis-driven reasoning (as they were taught) than were students in a traditional curriculum. In two studies, students in independent learning curricula transferred the scientific reasoning strategy to unrelated problems and generated more coherent explanations than students without independent learning experience (Hmelo, 1998; Hmelo *et al*., 1997).

2.7.2 Creative Thinking

Creativity has often been seen as part of science education and attempts to describe it have been made by numerous scholars. Rickards (1990) described creativity as escaping from ‘stuckness’ and finding new possibilities, whilst Yager (2005) said that creativity is the ability to generate new ideas, possibilities or inventions based on originality in their production. Moravcsik (1981) stated that creative thinking is bringing purpose to the use of basic thinking operations to expand or create new ideas. Visualizing, producing mental images, combining objects and ideas in new ways, producing alternative or unusual uses for objects, solving problems and puzzles, suggesting viable explanations for objects and events in nature, designing tests to verify explanations of visualizations, designing devices and machines, producing unusual ideas, and communicating information to others for which evidence has been produced and illustrated are all important human abilities in which creativity can become apparent (Yager, 2005).

In this current research study, creativity refers to students’ ability to find a variety of input ideas in multiple perspectives to create a new solution to a stated problem. Clearly, creative thinking must be based on the manipulation of learners’ experience and existing knowledge. This definition is closest to the definition of creativity used by Rickards (1990).

Independent learning activities have been claimed to improve creative thinking particularly through research activities using a diverse range of scientific observations, by making classifications, asking questions of scientific research, forming hypotheses, planning trials and methods of measurement, using equipment or appliances, and making conclusions from empirical data (Cheng, 2011). Aksoy (2005) found that a teaching strategy which is based on the scientific method process in creative thinking increased the creative thinking level of the participating students, improved their academic success level and advanced their attitudes to the lessons teaching science knowledge. Similarly, Korotov (1992) claimed that independent learning allows learners to become self-disciplined and creative. In addition to Korotov, many other scholars (Boekaerts, 1997; Anthony, 1994; Zimmerman *et al*., 1996; Zimmerman, 1998; Weiss, 2004) have cited thinking creatively as an additional benefit of teaching approaches which promote independent learning. Allan *et al.* (1996) studied a number of research projects on the development of independent learning and found a range of positive outcomes associated with being an independent learner, including students being more likely to be more original and creative.

Cheng (2006) and Hu and Adey (2002) presented comprehensive strategies to provide creative learning in science education, particularly in physics teaching. Both of these strategies promote independent learning as it involves activities such as project-based learning or problem-based learning. In addition to these, Kind and Kind (2007) also found that independent learning might contribute to creative thinking in the context of science education. Their instruction suggestion included an open inquiry, creative problem solving, creative writing, metaphor and analogy.

Furthermore, it was claimed that teaching approaches that include individual activities might be particularly beneficial for improving creative thinking as the peer group has been found to be the main obstacle that caused learners to refuse to take risks and express their creative ideas (Sternberg & Lubart, 1996; Torrance, 1963; Amabile, 1996).

2.7.3 Self- Assessment

As with any profession that operates under the principles of independent learning and autonomy, the competent scientist, in particular the competent chemist, must be an independent, lifelong learner (Moore & Cordes, 1992). The first step in this process is the diagnosis of one’s own learning needs, which enables the formulation of appropriate learning goals (Spencer & Jordan, 1999). Therefore, the ability to accurately assess one’s own strengths and weaknesses is critical to the enterprise of lifelong learning (Gordon, 1992). Theoretical argument for the critical significance of self-assessment has led many scholars to create instruction strategies which might improve learners’ self-assessment abilities.

Independent learning has been associated with a variety of concepts related to self-assessment, including autonomy, motivation, taking responsibility, reflection, goal setting, time management, self-regulation, metacognition, self-awareness and self-direction (Garrison, 2003; Hurd, Beaven & Ortega, 2001; Peters, 1998; White, 2003). In the past, the majority of research studies in self-assessment were carried out in distance-learning environments, but more recently classroom applications have gathered more attention (Benson, 2001; Gardner & Miller, 1999; Murray, 2004). It is possible to claim that more work has been done in medical schools and language learning compared with other areas of education about self-assessment.

Traditional self-assessment studies focus on the individual's ability to rate him/herself relative to peers (Ward, Gruppen & Regehr, 2002). However, mainly due to methodological problems, more recent studies have called for a redefinition of the term 'self-assessment'. Regehr, Hodges, Tiberius & Lofchy (1996), for example, suggested that self-assessment should emphasize each learner's ability to focus on the relationship between his/her own strengths and weaknesses. Gruppen *et al.* (1997, 2000), similarly, made a distinction between the idea of self-assessment as an inter-individual process or as an intra-individual process. Consideration of self-assessment as an intra-individual process has usually been claimed as a methodologically superior perspective (Fitzgerald, Gruppen & White, 2000). In this current research study, therefore, the focus will be on the impact of the promotion of independent learning on students' ability to identify their own strengths and weaknesses (the intra-individual process).

Malone and Smith (1996) stated the importance of students being able to reflect on their achievement, monitor their progress and use self-assessment for independent learning because this ensures that students take responsibility for their own learning. As independent learning stimulates the active engagement of learners in the learning process by using both cognitive and metacognitive strategies, it also promotes self-assessment abilities (Chinn & Brown, 2002; Windschitl, 2002). Moreover, Davis (2003) claimed that independent learning settings promote self-assessment as a key component of metacognition. There is also empirical evidence which emphasizes the benefits of independent learning approaches for self-assessment, even though they might be considered weak (Benson, 2007).

2.8 Summary and Conclusion

The introduction to this chapter claimed that the literature review would have two main objectives. The first objective was to define the context and focus of the study as well as to provide information about the reviewed literature on innovative instruction strategies which aim to promote independent learning and the possible problems related to these research studies in science teaching. From the first part of the chapter, it can be concluded that although the usual approach to teaching chemistry at university is still traditional, lecture-based instruction, over the last few decades there has been an extensive movement internationally to change higher education chemistry teaching through a range of innovative teaching approaches which aim to promote independent learning. In this research study, an instruction strategy which has similar aims to other instruction strategies reviewed in this chapter will be investigated. Its impacts on students' knowledge of and understanding about various ideas, and the improvement of some of the students' intellectual attributes will be discussed.

Drawing on the research reviews of independent learning in the science education literature, the following points can be summarised.

- There are internal and external elements at the core of independent learning which play a significant role in the success or failure of the teaching approaches which aim to promote independent learning. The internal factors are the cognitive, metacognitive and affective skills which learners must have or acquire. The external factors are the relationship between the lecturers and the students and the enabling environment which supports the development of independent learning.
- Students do not become effective independent learners on their own; independent learning should be promoted (and/or taught) by the lecturers for students to learn how to learn.
- In the literature, suggested strategies to promote independent learning include scaffolding, allowing students conditions to self-monitor, modelling of behaviours, providing constructive feedback and using ICT appropriately.

- If applied carefully, independent learning can have numerous benefits to students including increased academic achievement, improved motivation and confidence, and more individualised learning opportunities, giving the fundamentals for being life-long learners and a more satisfying learning experience.
- The vast majority of the literature that shows the mentioned benefits of independent learning are from complex teaching approaches which makes it hard to attribute all these mentioned benefits to independent learning itself.
- Little research is available about the views of students and lecturers of independent learning.

Considering the requirement that education should prepare learners to be life-long learners in science, possibly in all subjects, independent learning has massive significance for every student, particularly considering its claim to help individuals to construct their own knowledge and develop higher-order education aims such as scientific reasoning, creative thinking or self-assessment. It can easily be claimed that scholars in the science education domain are currently making great efforts to create life-long learners by applying innovative teaching approaches which aim to promote independent learning in higher education. Project-based learning, problem-based learning, moving in-class modules online, flipped classrooms and ICT-based courses are the most common of them. Previous research studies have suggested that when teaching strategies which aim to promote independent learning are implemented appropriately in particular contexts, students can have a variety of benefits. However, more research needs to be done to investigate attempts such as the Macromolecules course in order to be able to understand what works, what does not work and how. This kind of research can contribute to both the theory and the practice of the instruction strategies that promote independent learning.

The second objective was to outline the research studies related to students' understanding of specific chemical ideas related to polymer chemistry in order to provide a background for a better understanding of what has given rise to the issues that will be further discussed later on in the following chapters. The second part of this literature review has two main headings. The first is related to students' misunderstandings. This section suggests that the understanding of students about some aspects of chemical ideas is unlikely to be well-developed and that some misunderstandings will necessarily exist. The reasons behind those misunderstandings can vary. Students may have developed some kind of explanation before they come to the science classroom and those ingrained explanations can seriously hamper their understanding of scientific explanations. In addition to their everyday life explanations, students' lack of scientific vocabulary, their lack of comprehension at the three levels of chemistry (macroscopic, sub-microscopic and symbolic) and the transition between them may be some of the reasons for their misunderstandings in those polymer chemistry-related ideas. In conclusion, the second part of this chapter suggests that students are likely to have some misunderstandings about the ideas investigated in this research study. Furthermore, the improvement of students' understanding is or should be the core of science education. The other heading of the second objective is related to students' intellectual attributes. This section defines the intellectual attributes investigated in this research study and shows some evidence that independent learning can contribute to the improvement of those attributes.

This chapter has provided a literature review about independent learning as independent learning is used as the theoretical framework of the course investigated in this research study. The next chapter will describe the course investigated, present the course leader's reasoning in facilitating the Macromolecules course with the independent learning approach and map these against the literature reviewed in this chapter.

Chapter 3: Identification and the Context of the Teaching Strategy

Introduction

As will be explained in the methodology chapter, Chapter 4, this research study takes the form of a case study. Case study research is discussed in detail in the methodology chapter, and it is concluded that one significant merit of case studies in education is that they provide sufficient context for readers to understand and re-apply the investigated subject which is a teaching approach which aims to promote independent learning in this research study. It is argued in the literature widely that case studies can be transferred to practical applications relatively easily (Bassey, 2000). This current chapter serves the purpose of providing sufficient information about the context of the case study for readers to evaluate the study in its specific context and apply it if it is appropriate and necessary. In addition to this, the chapter has three main purposes. First, it aims to explain fully how the Macromolecules course was identified and why it was chosen as the focus of this research study. Second, this chapter aims to map the Macromolecules course's teaching approach against the literature reviewed in the previous chapter. Finally, this chapter aims to present the rationale behind the shift from traditional teaching approaches to independent learning methods in tertiary level chemistry education. With those key features, this chapter is crucial for the understanding and further application of the investigated teaching approach and the clarification of this research study.

3.1 The Subject of the Research Study

At the beginning of this section it seems appropriate to give a full explanation of how the course which was chosen as the focus of this research study was identified. In the previous chapter, the literature review, it was concluded that there is a consensus concerning the importance of promoting independent learning through a variety of teaching strategies, particularly in higher education. This has led informed and innovative chemistry educators to building up a repertoire of strategies to promote independent learning and gradually engage students in becoming more independent in their learning. Whilst the usual approach to teaching at university is still traditional and mainly lecture-based in many of the higher education institutions, in others, particularly those which are lucky enough to hire informed and innovative lecturers, there are various attempts at creating and applying teaching strategies which aim to promote independent learning. Although such approaches may well still represent a small minority of courses in higher education, it is extremely important to study them in order to both improve the teaching practice of similar approaches and inform the educational theories related to independent learning.

3.1.1 Identification of the Course

The course which was chosen as the focus of this research study is a Macromolecules course in the Department of Chemistry. The course is a compulsory course for enrolled BSc and MChem students and it is delivered during the spring term of the first year. There were four main reasons for choosing the Macromolecules course as the focus of this research study. First, the Macromolecules course is an 'independent learning' course in university-level chemistry education. It is an innovative teaching approach to tertiary-level chemistry in which students take responsibility for their own learning. The course does not include any lectures but it provides materials and support for the independent learning activities of students. Second, the learning objectives of the Macromolecules course include not only objectives relating to the knowledge of and understanding about chemical ideas about polymers, but also objectives relating to the development of independent learning abilities. Third, it was established in the literature review (*see* Chapter 2) that the majority of research studies about independent learning have investigated teaching approaches which employ independent learning methods blended with other teaching approaches. Hence, the findings of these research studies are hard to interpret due to difficulties of isolating the impact of independent learning strategies from the impact of other used teaching strategies. However, the entire Macromolecules course is taught by the independent learning approach, hence the findings which emerge from its investigation can be confidently related to the independent learning approach. Finally, it is a compulsory course in the department of chemistry for first-year students. Hence, implications which emerge from its investigation can have a direct impact on its practical application. The teaching approach of the course was first presented in a staff and postgraduate student seminar about teaching approaches in higher education as an attempt to promote independent learning in the university in which it is currently being taught. It was first identified at this seminar.

3.1.2 The Macromolecules Course

The Macromolecules course is an independent learning course in university-level chemistry education. The course has been taught since the academic year of 2010/11 to first-year chemistry undergraduates using an ‘independent learning style’, as the course leader calls it. In the past, the same course had been instructed in the traditional lecturing style. The investigated sample of students studied the course in the spring term of the 2011/12 academic year. The course provides a solid grounding in macromolecular science, and also acts as a foundation for the second- and third-year courses *The Materials World 1* and *2*, which explore in more detail the ways in which chemists develop new materials.

The Macromolecules course, in the department in which it is being facilitated, is unique amongst students’ first-year courses in being taught in an independent learning style. ‘Independent learning style’ was the particular name picked by the course leader in order to emphasize that students are asked to work alone to find solutions for the given problems and tasks and that this course was intentionally designed to promote independent learning. In this course, students are expected to take responsibility for their own learning just like the reviewed teaching strategies in the previous chapter.

The course has two major parts. In the first part, students are given a workbook (*see* Appendix 1) which was prepared by the lecturer. The workbook was based on the lecturer’s previous lecture notes which had been adapted to fit in with the principles of independent learning. These principles will be explained in detail later in this section. The students are asked to start by working through this workbook, reading the sections, finding further information via weblinks and so on, and then to attempt to answer the problems which are expected to guide students' learning of the topic.

If they had problems with the work, they had access to a discussion board forum on the VLE in order to ask any questions. Hence, for this first part of the course the participating students were receiving guidance from their lecturers whenever they encountered a problem. They could find the Macromolecules Discussion Board forum by following the link to Year 1: Core Chemistry 2: Analysis, Structure and Bonding and then clicking on the 'Discussion Board' on the left-hand toolbar. Once they had worked through the first part of the course in this way, they were asked to attempt the assessed tutorial questions. These questions were designed to test the depth and breadth of their learning. Students were allowed to use whatever resources they chose to help them to answer the problems but they were not allowed to request answers to the tutorial questions on the discussion board. The first part of the course can be easily associated with problem-based learning as the problems presented to students are used as a tool to achieve the required knowledge and moving in-class courses online as whole content of the course was also transferred to on-line learning environment.

For the second part of the course, students were asked to carry out an independent investigation into an aspect of polymer chemistry, and then present their findings in the format of a written article or short video. The polymer chemistry topics were assigned by the lecturer in the introductory lecture. The topics given to the students can be found as Appendix 2. The students were asked to present their findings from this investigation as either a written magazine-style (*New Scientist*/*Chemistry World*) article (1500 words max, plus illustrations) or as a YouTube style video (5-10 minutes). If they wrote an article, this was handed in to their college tutor at the start of the summer term. If they made a video, students were asked to publish this on YouTube (or other equivalent freely-accessible video sharing site) and to give their tutor the weblink at the start of the summer term. Students had a free choice of which kind of presentation they could make. However, to encourage them to make a video presentation, the lecturer offered prizes (Amazon vouchers) for his favourite videos, and for any videos which had generated lots of comments/discussion on YouTube by the end of week 9 of the summer term. The reason behind this encouragement was the expected low number of students who would prefer to make a video presentation. Their articles/videos were assessed by their college tutor. The marking schemes and marking criteria can be seen as Appendix 3. This component of the Macromolecules course can be best associated with project-based learning since students pursue knowledge by asking questions that have piqued their natural curiosity. However, usually in project-based learning environments teachers have a mentor or guide role, and in the second part of the Macromolecules course students were left on their own to pursue knowledge.

Once they had completed both parts of the course, they then attended a workshop in which they received feedback on their performances and discussed the issues they had encounter during their personal investigations. This part of the course is very similar to activities in flipped classroom instruction in which students do their given tasks outside the lecture environment and they come to the lecture environment to receive feedback and discuss their findings.

In the next section, the strategies that were employed to design the Macromolecules course which incorporated instruction strategies which promote independent learning will be discussed.

3.1.3 How Does the Macromolecules Course Promote Independent Learning? Mapping the Macromolecules Course against the Literature

It has been explained above that the Macromolecules course has two parts, one in which students use an interactive booklet to follow and find their own solutions to problems given with guidance provided via a discussion board, and a second in which students conduct a personal investigation and present their findings without receiving any guidance until they present their findings. In this section, how the Macromolecules course promotes independent learning will be explained by referencing it to the literature covered in the previous chapter.

As has already been stated, the promotion of independent learning requires a new role for educators, which is based not on the traditional transmission of information, but on student-centred teaching, which ensures that students are actively involved in the learning process. In the Macromolecules course, students' active engagement with the learning process can be demonstrated in both parts of the Macromolecules course. During the first part of the course, the students were asked to go through the workbook prepared by the course leader. This booklet was completely interactive; sections in the booklet start with a piece of information but frequently in the booklet students reach a section where they are told ‘You do the work’. This might be something useful to look up online, it might be a calculation that students needed to do, or something that they needed to work out about polymers, and by working through the booklet and solving the problems, they were expected to find the solutions and prepare themselves for the assessment at the end of the course. It was suggested in the literature that students’ motivation in independent learning strategies can be increased by ensuring that the tasks provided during independent learning are based on realistic scenarios that students can relate to in their everyday lives (Marx *et al*., 1997). To achieve this, the ‘You do the work’ parts of the booklet were primarily based on realistic scenarios. The booklet contained the whole syllabus of the course. Basically, it was the lecturer’s old lecture notes which he had used to deliver this course in an in-class lecturing style, but with new pictures, better explanations, and many more interactions for students to work around. The workbook had enough working space for students to write their results and it frequently required the engagement of students with scientific phenomena. Montalvo and Torres (2004) proposed that in addition to observing teachers, students could also be encouraged to observe other expert models, such as more experienced peers. In order to increase the element of students modelling their more experienced peers, in the discussion board tutors did not give instant replies to students’ questions but waited for another student to write an answer to other students’ questions. The usual allowance for a question was about six hours. If there was no response by other students, tutors then gave the correct answer for the question. That responding flexibly to students’ questions and responses rather than following a predetermined teaching path also fits in with the requirements of guidance which is assumed to promote independent learning (Myhill & Warren, 2005). Moreover, it is claimed that asynchronous communication is successful at promoting independent learning (Garrison & Anderson, 2003) due to it providing learners with opportunities for critical reflection which is necessary for higher-ordered learning goals such as critical and creative thinking.

The responsibility of the tutors in the discussion board was to behave like a mentor (Malone & Smith, 1996), to understand how students think and to guide them towards independence. The role of tutors as mentors involves them relaying their enthusiasm about a topic to students, and encouraging students to make enquiries for themselves. Therefore, in the discussion board, tutors provided opportunities for students to make these enquiries, for example by encouraging students to ask challenging questions or verbally rewarding them when they did so.

During the second part of the course, the students were asked to carry out an independent investigation of a polymer chemistry topic that they were interested in. The independent investigation offered students eleven different contexts to choose from, all of which were related with polymer chemistry. As mentioned in the literature, student choice is a key element of the independent learning approaches (Bell, 2010). The aim of this investigation was to improve students' knowledge and understanding of a variety of ideas including recycling, intermolecular bonding, polarity, isomerism and biocompatibility as well as improving their independent learning skills. The investigation contexts were phthalates applications such as children's toys, plastic packaging, a Nobel prize for polymers, living polymerisation, reliance on oil, biocompatible polymers, polymers in high technology, plastics and recycling, polymers in fashion, polymers in the aviation and space industry, and polymers in sports, but students were also allowed to choose a topic of their own if they could come up with an even better idea related to polymers. They were also informed about the ideas that they were expected to focus on during their investigations; just like the 'You do the work' parts, all the investigation topics were contextualised. As mentioned earlier, fostering motivation, and recognising and appreciating success is necessary (Van Grinsven & Tillema, 2006). This element of motivation was constantly satisfied by tutors by verbal appreciation of every created piece of presentation from students. In addition to verbal appreciation, some material rewards (for instance, gift cheques for the best videos and articles) were given for the success of students. Moreover, as has been suggested in the literature (Page, 1989), students should actively and creatively engage in the production of ICT resources for learning. They were asked to create their own videos or journal articles at the end of their individual investigations which ensured their active participation in the production of ICT sources. Those ICT sources can then be used to teach other students or inform the wider public (*see* Smith, 2014). In this second part, the students did not receive any guidance during their independent investigations until they submitted their presentations.

Taking responsibility for learning, active participation and motivation which are considered to be the essential requirements for promoting independent learning (Minner, Levy & Century, 2010) were all present in the settings of the Macromolecules course. As already explained, there were no lectures, except the introduction lecture in which the teaching strategy of the course was explained, nor was any other type of instruction employed during the Macromolecules course. The entire course depended on students' responsibility for learning, hence the findings of this research study can easily and confidently be related to the impact of the independent learning strategy. Students were asked to work through the workbook on their own, answer VLE questions on their own and work on their independent investigation in order to find solutions to the problems and tasks given. They were required to pick their topic (question), organize their investigation (design), collect data from numerous sources including scientific journals, books and weblinks (data), come up with their findings or summarized ideas (conclusion) and present and discuss them in either a video or a journal article format (communication). In the Macromolecules course, the students had the opportunity to choose how, when and where to learn. In addition to independent investigation, in the first part of the course, the 'You do the work' parts in the workbook were all designed to fit into some part of the investigation cycle (question, design, data, conclusion, communication). This investigation cycle has been suggested as an affective model for promoting independent learning through inquiry (Minner *et al*., 2010).

All these features of the Macromolecules course lead to the conclusion that the Macromolecules course uses a teaching strategy which aims to promote independent learning. As concluded in the literature review, the investigation of the teaching approaches which aim to promote independent learning is essential in order to improve both the theory and the practice of independent learning strategies. Hence, the Macromolecules course was chosen as the subject of this research study.

3.1.4 The Learning Objectives of the Macromolecules Course

The main assumption of the course leader in creating and applying the Macromolecules course in the independent learning style, as was highlighted during the introduction lecture of the course, is that "by taking responsibility for their own learning in this course, students will develop a number of key attributes such as time management, self-assessment, creative thinking, and scientific reasoning, as well as coming to a good understanding of the topic itself". The independent nature of the assignment is also expected "to help them to develop writing, presentation, and IT competencies". At this point, it is appropriate to present the learning objectives of the Macromolecules course; these objectives were created and used by the course leader in assessing the students for their degree.

Table 3.1 presents the learning objectives of the Macromolecules course. These learning objectives were also presented to the students during the introductory lecture to the course and given to them as part of their independent learning package.

Learning Objectives of the Macromolecules Course	
1	To appreciate the importance of Macromolecules.
2	To appreciate the wide use of Macromolecules in everyday life.
3	To be comfortable with the statistical nature of polymer chains and to be able to calculate M_n and M_w values for model polymer distributions.
4	To understand the features of polymers based on synthesis and structure.
5	To know some methods used to measure M_n and M_w and to understand the information they provide.
6	To understand how structural features control the physical features of the polymers.
7	To understand the principles behind gel permeation chromatography and to use model data to calculate molecular masses.
8	To understand chain growth mechanisms by which polymers can be synthesised and their implications.
9	To comment on the outcomes of polymerisation reactions based on a mechanistic understanding.
10	To be able to draw and interpret some isomer structures of polymers.
11	To understand the biodegradability and biocompatibility features of polymers.
12	To be familiarized with common functional groups of polymers used mainly in medicine.
13	To understand how crosslinked polymers can be synthesised and how their properties can be controlled.
14	To understand the possible side effects of polymer applications such as chelate forms.
15	To have an introductory grasp of the structures of some inorganic polymers.
16	To know, and be able to comment on, some high performance applications of Macromolecules.
17	To develop independent learning skills such as self-assessment, creative thinking, scientific reasoning.
18	To develop presentation skills – either writing skills or oral video presentation skills.

Table 3. 1 : Learning Objectives of the Macromolecules Course

In particular, these learning objectives can be separated into three groups.

Learning objectives related to knowledge acquisition:	
1	To appreciate the importance of Macromolecules.
2	To appreciate the wide use of Macromolecules in everyday life.
5	To know some methods used to measure M_n and M_w and to understand the information they provide.
12	To be familiarized with common functional groups of polymer used mainly in medicine.
16	To know, and be able to comment on, some high performance applications of Macromolecules.
Learning objectives related to understanding:	
3	To be comfortable with the statistical nature of polymer chains and to be able to calculate M_n and M_w values for model polymer distributions.
4	To understand the features of polymers based on synthesis and structure.
6	To understand how structural features control the physical features of the polymers.
7	To understand the principles behind gel permeation chromatography and to use model data to calculate molecular masses.
8	To understand chain growth mechanisms by which polymers can be synthesised and their implications.
9	To comment on the outcomes of polymerisation reactions based on a mechanistic understanding.
10	To be able to draw and interpret isomer structures of polymers.
11	To understand the biodegradability and biocompatibility features of polymers.
13	To understand how crosslinked polymers can be synthesised and how their properties can be controlled.
14	To understand the possible side effects of polymer applications such as chelate forms.
15	To have an introductory grasp of the structures of some inorganic polymers.
Learning objectives related to independent learning skills:	
17	To develop independent learning skills such as self-assessment, creative thinking, scientific reasoning.
18	To develop presentation skills – either writing skills or oral video presentation skills.

Table 3. 2 : Learning Objectives of the Macromolecules Course in Three Categories

The same learning objectives were also used to create the diagnostic questions and every diagnostic question in the pre-test, post-test design was related to one of the learning objective of the Macromolecules course presented above (*see* Table 3.2).

3.2 The Rationale for Promoting Independent Learning through the Macromolecules Course

The Macromolecules course is a fundamental course in university-level chemistry education. Polymers are perhaps the most important materials of the last century and it could be easily claimed that they are now the most commonly used materials in many industries. Considering their significance, every modern university-level chemistry course pays the utmost attention to supporting high-quality teaching about polymers as well as many other chemistry subjects. After the original inclusion of the Macromolecules course in the chemistry programmes in the university in which this research study was undertaken, the course had been taught in the traditional lecturing style. In the academic year of 2010/11, however, the teaching approach was switched to the ‘independent learning style’. The course leader’s reasons for this change which emerged from the data generated from the interviews with lecturers and from document analysis (*see* section 4.2.8) were that the independent learning approach applied in the Macromolecules course was a response to the changing student profile in higher education, it was a response to changing expectations from modern chemists, it was a chemical research-led and educational research-led approach and it was an attempt to show chemistry as a ‘cool’ subject and chemists as ‘cool’ people. In the first part of this chapter, the rationale behind the shift from the traditional teaching approach towards the independent learning approach of the course leader will be explained and they will be mapped against the literature reviewed.

3.2.1 A Response to the Changing Student Profile in Higher Education

The development of the world-wide web and the increasing use of multimedia and hypermedia have led to huge growth in the importance of these resources. The impact of these technologies on students' lives has also increased in importance and students have significantly changed some of their behaviours in the higher education context. For instance, nowadays it is not unusual to hear from students the response "let's 'google' it" if a lecturer cannot give a satisfactory response to their questions. It seems to be the case that students' familiarity with the internet and computer technologies affects their perceptions of access to knowledge. The traditional teaching approaches, such as lecturing, are evidently not enough to respond to a new generation of students who have grown up with digital and cyber technologies, and new instructional approaches need to be developed and applied, especially in tertiary level education where students have the most freedom and courage to express their needs.

On average, an American student who was born in 1982 or later will, by the age of 21, have spent 10,000 hours playing video games, 20,000 hours watching television, 10,000 hours on cell phones and under 5,000 hours reading, and will have sent and received 200,000 e-mails (Bonamici *et al*., 2005). As a result of this change in the media with which students interact, they have developed distinctive ways of thinking, communicating and learning compared with students of previous generations (Oblinger & Oblinger, 2005; Prensky 2006; Tapscott, 1998).

Carlson (2005) argued that new-generation, net-literate students are more assertive information seekers and that this shapes how they approach learning in the classroom. Today's students are more conscious about which learning techniques work best for them, and which can include reading lecture notes online, viewing interactive media such as PowerPoint presentations or digital images, or working in groups. His arguments have been widely supported by others. Oblinger and Hagner (2005) observed that digital-age students express a need for more varied forms of communication and report being easily bored with traditional learning methods. Glenn (2000) noted that internet-savvy students need independent learning opportunities, interactive environments, multiple forms of feedback and assignment choices that use different resources to create personally meaningful learning experiences, whilst Hay (2000) found that new-generation students want more hands-on, independent learning approaches and are less willing simply to absorb what is put before them. Tapscott (1998) argued that this need for an independent learning style has grown out of the ingrained habits of seeking and retrieving information from the internet, which marks a striking contrast to previous generations of students who tended to acquire information more passively from authority figures. This shift in the student profile requires an adjustment in teaching strategies. Howard (2006) suggested that students of this new type acquire information by developing their own questions, systematically evaluating sources and selecting evidence to support their answers.

In the light of the studies discussed above, the development of new instructional approaches is a necessity for the future of higher education, especially considering the likelihood that future generations will continue to be at the forefront of technological changes. It can easily be claimed that the growth in the number of students who were brought up in the context described above will continue. Hence, it can be expected that the need for instruction strategies which allow students enough space to be information seekers and decision makers will be even more pressing in the near future. Regarding the expected features of a teaching strategy which fulfils the needs of new-generation students in higher education, possibly the most appropriate theoretical framework is independent learning. Hence, the first reason for facilitating the Macromolecules course with independent learning strategy was to respond to the changing student profile in higher education and to create a course which responds to students' needs more accurately than the traditional lecturing approach.

3.2.2 A Response to Changing Expectations from Modern Chemists

For the last three decades in chemistry education in particular, there have been many calls for reform. However, the curriculum for first-year undergraduate chemistry at many universities across the world is still mostly fact-based and encyclopaedic, built upon a collection of isolated topics, oriented too much towards the perceived needs of chemistry majors, focused too much on abstract concepts and algorithmic problem solving, and detached from the practices, ways of thinking and applications of both chemistry research and chemistry education research in the twenty-first century (Talanquer & Pollard, 2010).

In the recent past among scientists, the speed of the retrieval of information has made a significant difference as finding a piece of information was previously a much more complex and time-consuming process. So having the knowledge in one's mind was a significant advantage. Considering this argument, having a chemistry curriculum that covers as much factual knowledge as possible might have been accepted as quite a sensible approach for undergraduate chemistry education in the past. On the other hand, nowadays the expectations from modern chemists have significantly changed. The expansion of the internet has made it possible to reach almost any piece of information with barely any effort. For chemistry specifically, to find any balancing chemical equations, stoichiometric equations, electron configurations, Lewis structures, chemical structures, electronegativity values, compound structures, isomer structures and so on is now as easy as typing a query into the right search engine on a computer with access to the internet. Bearing this in mind, committing to memory all the knowledge that students can easily reach does not seem to be a valuable strategy for a successful chemist. Saying that clearly does not, however, mean that modern chemists do not need a foundation of sound knowledge, but with the changing ways of accessing knowledge, chemists are required to develop different abilities. After all, the handicap of having such a massive amount of knowledge accessible on the internet is that it requires skills to determine exactly what is required from an almost endless pile of knowledge and then to interpret it sensibly. Moreover, the advantage of being a chemist is not just having a piece of knowledge about some chemistry subject, but more about shaping the way one looks at and thinks about the world. In a broader sense, chemistry can be seen as a quest to reveal the identity of substances, to understand the diversity in the material and biological world, to explain similarities and differences, to transform nature, and to create in ways which many might consider impossible (Hoffmann, 1995). So the way that chemists think, build and use models, represent systems and processes, observe appropriately, design experiments, interpret findings and generate explanations, and correlate findings with other problems and explanations are the types of knowledge and skills that undergraduate chemistry students will find useful and be able to utilize in their future studies and work. Current research studies on curriculum design support the view that those attributes and types of knowledge are likely to be needed by students in their future lives and work (Mbajiorgu & Reid, 2006). So the question which remains is how we can prepare learning environments in which students can improve those intellectual attributes and learn the required type of knowledge. Clearly, the traditional knowledge-based education system is not sufficient to achieve this goal and fails to prepare students for chemistry careers in today's modern world.

One significant attempt in science education to equip students with these new competencies and improve their understanding of the world around them by engaging their natural curiosity is context-based education. Context-based chemistry teaching can be described, in its most basic form, as teaching chemical principles and concepts in a way which relates them to students' everyday life experiences. Three main aims of context-based education can be discerned: to provide students with more interesting lectures, to improve the science learning process by increasing the engagement which is stimulated by the increased interest in science and lectures, and to provide scientifically literate people who can make sense out of some of the science which is related to their everyday lives (Bennett & Holman, 2003). Innovative context-based approaches and materials have been designed, applied and assessed intensely over the last ten years. The literature is replete with research studies which have identified significant increases in students' interest and engagement (Bennett *et al*., 2006; Gilbert, 2006; Gutwill-Wise, 2001; King, Bellocchi & Ritchie, 2007; Ramsden, 1997; Schwartz, 2006). There are also some research studies that have shown improvements in students' understanding and performance regarding in-depth knowledge (Demircioglu, Demircioglu & Calik, 2009), although they can be considered weak in comparison with the results of studies related to students' engagement and interest.

The context-based approach, however, is criticised on the grounds that personal differences between teachers and difficulties related to the extent of teachers' professionalism play a significant role in the success of the teaching approach (Vos *et al*., 2010). Considering the high amount of face-to-face interaction between teachers and students, the impact of personal differences between teachers is hugely significant in the context-based teaching approach. One possible solution could be to reduce the amount of face-to-face contact time between teachers and students. In 2009, a study carried out by SRI International for the US Department of Education concluded that students in on-line learning conditions performed better than those receiving face-to-face instruction (Means *et al.*, 2010). There was no specific analysis of context-based approaches compared with other approaches in that meta-analysis study, but even so, reducing the face-to-face interaction time in context-led approaches may be an improvement as it decreases the impact of personal differences between teachers and the difficulties related to the extent of teachers' professionalism. So the use of context-based approaches in independent learning settings is a topic which needs to be studied.

Another criticism of context-based teaching is that it encourages 'dumbing-down' and that future scientists will suffer from the lack of factual knowledge. It is true that context-based approaches that cover a smaller syllabus usually require more time to apply, yet the depth of learning should be the concern rather than the amount of factual knowledge covered in science education. The main reason for this suspicion is the supposed decrease in the difficulty level of science examinations. Richard Pike, Chief Executive of the Royal Society of Chemistry, has criticised the examining boards in the UK, saying that, "A number of questions could be answered merely from reading a national newspaper every day, as the scientific content was minimal and general knowledge would have been sufficient" (Agbenyega, 2009). The question which should be answered now is 'What do we really want to teach our students?' If we want them to know everything we know as chemists, then an approach that covers the greatest amount of factual knowledge might possibly be the best option. On the other hand, if we want students to comprehend our way of thinking as chemists, the teaching approach should focus on this issue rather than on conveying a specific amount of knowledge.

Comprehension of a chemist's way of thinking is a strong statement and there is no doubt that it is very hard to achieve. However, it can be claimed that if there is one way to achieve this goal, it should somehow include student independence. Every successful chemist, possibly every successful human being, is an active and independent learner to some degree. In the modern world, the success of chemists is highly related to their ability to take responsibility for their own learning and their abilities at adapting their thinking to different problem contexts. So in chemistry teaching, it is vitally important that we teach students to become active and independent learners who can take responsibility for their own progress, rather than relying on an instructor to show them the right way. Hence, teaching approaches which embed context and employ independent learning strategies can improve chemistry education particularly at tertiary level.

As discussed above, the expected intellectual attributes of a chemist (perhaps of scientists in general) have changed and independent learning approaches may be productive ways to develop the attributes required of a chemist. The second reason for changing the teaching strategy of the Macromolecules course to independent learning was to adapt teaching strategies at tertiary level to the changing expectations of the industry from modern chemists. This in return may contribute to the better preparation of chemistry undergraduate students for their future professional life.

3.2.3 Chemical Research-led and Educational Research-led Teaching

When compared with secondary-level science teaching, there has been relatively little research over the past few decades into the impact of the teaching and learning of science in tertiary-level education (Childs, 2009). The diversity in the ability and backgrounds of the new student population at university level, their competencies in maths and science, and their motivation are changing rapidly. Many lecturers have not adapted sufficiently to the changes in the student population in tertiary-level education and it is a considerable challenge for them to apply evidence-based chemistry teaching. Evidence-based chemistry teaching refers to the actual practice of teaching chemistry at universities being shaped by the research evidence. It is quite ironic that chemists, and scientists in general, who inherently apply experimentation in their subjects, seem quite reluctant to do so when it comes to applying a scientific approach to teaching itself (Reid, 2008). However, students in higher education value research-led teaching and learning strategies, and this appreciation in turn may increase their engagement and enhance their learning (Zamorski, 2002).

When research-led teaching is mentioned in tertiary education, what is usually understood is the teaching informed by subject-based research. A lecturer who incorporates current research practice into his or her own teaching is usually perceived to be a better teacher of that subject. The inclusion of the findings of current research studies in teaching is important for relating knowledge to its application and can help to contextualise the content. On the other hand, the understanding of research-led teaching seems quite meagre at university-level teaching, perhaps at all education levels, as the importance of educational research is ignored in this simple definition of the term. So perhaps it is more appropriate to broaden the meaning of research-led teaching and add educational research-led teaching to it. More efficient research-led chemistry teaching might only be achieved by merging the two approaches together, chemistry research-led teaching and educational research-led teaching. In the definitions used here, chemistry research-led teaching refers to the inclusion of current research in chemistry in teaching content and educational research-led teaching refers to the inclusion of the findings of current educational research into teaching practice. Effective research-led chemistry can only be achieved by the proportional combination of these two elements in teaching practice.

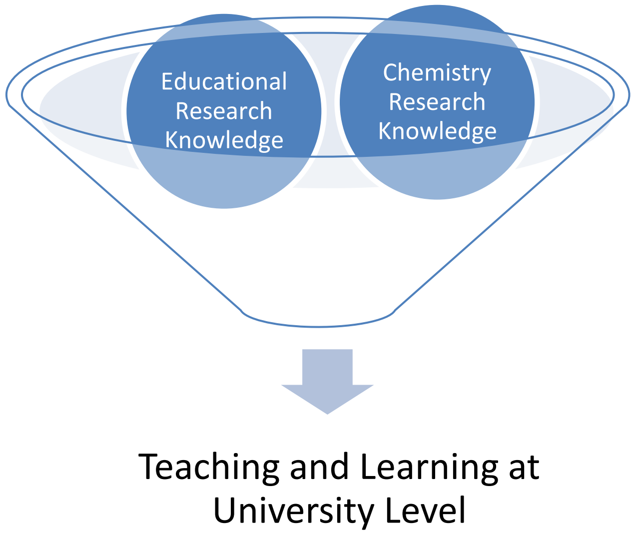


Figure 3. 1: Research-led Teaching at Tertiary Level

One further issue about research-led teaching in higher education is that it has often been discussed in terms of the merits that academic research can have on students' learning. However, the benefits flowing in the other direction (from the students to the researcher) are often not recognised. The link between research and teaching in higher education can be highly stimulating and influential for academics in their research and questions raised by students can open up whole new research areas (Smith, 2005). The benefits that teachers can gain from research-led teaching approaches have also been shown in more recent studies (Feldon *et al*., 2011).

In the light of these considerations, using chemistry research and educational research together can empower teaching practice in higher education. The third reason for changing the teaching approach of the Macromolecules course from lecture-based teaching to independent learning was to create an effective teaching approach which has benefits from both educational research and chemistry research. The teaching approach applied in the course has features from a few innovative teaching approaches including project-based learning, problem-based learning and flipping classrooms. This experimentation and progress in teaching may lead to profound improvements in educational outcomes.

3.2.4 Attitudes towards and Interest in Chemistry and Chemists' Image Problem

Students' attitudes are significant determinants of their levels of engagement and subject choice after students finish their compulsory study. For this reason, research interest in students' attitudes towards studying chemistry has been one of the significant areas in science education for the past few decades.

Moreover, considering the key arguments which support science teaching, the positive correlation between negative attitudes and the evidence of a decline in the numbers of young people pursuing careers in science, attitudes towards chemistry have become a subject of great concern among scholars. Some of the key issues which have been discussed are the economic, utilitarian and democratic arguments. The economic argument claims that we need a continuing supply of qualified scientists for industry and commerce; the utilitarian argument claims that we need to know some science in order to use equipment safely and to make informed decisions about health or lifestyle; the democratic argument claims that some science understanding is needed in order for us to take part in policy debates and reach an informed view on the issues being debated. In addition to these arguments, science can also be seen as a great achievement of our culture, and society should be helped to know about and appreciate it. Regarding all these valid arguments, the improvement of negative attitudes and the bad image of science and scientists, and of chemistry and chemists in particular, is of vital importance for all levels of chemistry education including higher education.

Previous research findings have shown that there are also widespread scientific ignorance and negative attitudes towards science in the general public (Durant, Evans & Thomas, 1989; Miller, Pardo & Niwa, 1997), and that even primary school teachers reflect similar attitudes (Royal Society of Chemistry, 1995). It is easy to claim that much has changed since the time that these reports were published. For instance, a recent report (Clemence *et al.*, 2013) showed that 58% of young people said they found school science lessons more interesting than maths; 58% also said they found science more interesting than English. However, still 31% of students were finding the subject too difficult and 24% of them were finding the subject boring. Even so, improvements can be clearly observed as 41% of the young people said they were personally interested in a future career in science, with no difference between genders. There were still many problematic issues such as that specific career interests were highly gender-stereotyped. For instance, the image of the stereotypical white-coated, male ‘mad scientist’ which emerged in early studies hardly seems to have changed. The interpretation of scientists and their work is now seen in a broader context, although the gender issue is still shown to be problematic in many studies (Haste, 2004). On the other hand, new characters introduced by the government show how embedded these ideas are in peoples’ minds. For instance, in an anti-drug campaign in the UK, a ‘crazy chemist’ tries to sell ‘dangerous chemicals’ to people (UK Government Web Archive, 2009). Usually the work of scientists appears to be valued and science is seen as important by students, but only a relatively very small percentage of them (21%) actually want to be a scientist. Students see science as important, but not for them (Jenkins & Nelson, 2005). When a sample of students were asked how they would describe a scientist, whilst over 60% used the adjectives ‘clever’ and ‘intelligent’, almost a quarter thought that scientists were boring and eccentric, and 93% of them said that they would not describe scientists as ‘cool’ or fun (Bennett & Hogarth, 2005). It is important to point out here that the samples in the majority of the previously mentioned studies were school children, however, the attitudes are shown to be resistant to change and some of these attitudes are being transferred to higher levels of education, including tertiary level and further. The main point of presenting such research studies is to show that some students at all levels of education have negative attitudes towards science and scientists. So science education at all levels should aim to change this negative perception of science among students and the general public.

The question to ask at this point is how we can teach chemistry to students so that they do not have these negative attitudes. Or if they already have them, how can we teach chemistry so that students can move away from those negative ideas about science and scientists? How can we make chemistry cool without compromising their education? To employ approaches which engage students with chemistry is at the centre of answering these questions. Independent learning is assumed to contribute answers to these questions. Independent learning is in general an attempt to improve the variety of intellectual attributes, including creativity. The reason for facilitating the Macromolecules course in the independent learning style was to show the creativity in chemistry, this is an attempt to make chemistry courses 'cool' courses, and an attempt to show that chemists can be 'cool' people. It is an attempt to move traditional chemistry lectures away from being dogmatic, structured, boring lectures to being engaging, creative courses in a way which can not only turn chemistry students into more active, independent learners with the chemical literacy required for innovative problem-solving, but which can also engage with the broader population and convince them that chemistry is an important and inspiring part of their lives.

3.3 Conclusion

In this chapter, the description of the course which is the subject of this research study, how the course was identified and chosen as the focus of this research study, key features and the learning objectives of the Macromolecules course and the rationale behind the shift from traditional teaching approaches towards independent learning approaches have been presented. In addition, all the key features of the course are mapped against the literature. In the results chapters, students' answers to the created diagnostic questions which are aligned with the learning objectives of the Macromolecules course will be presented. Drawing on the results generated from this research study, the level of success of the instruction strategy will be discussed in detail. The reasons behind the success or failure of the learning objectives will be addressed and discussed in the conclusion chapter.

Chapter 4: Methodology

Introduction and Re-presentation of the Research Questions

The purpose of this research study is to investigate the impacts of a tertiary level Chemistry teaching approach which aims to promote independent learning on students' knowledge, understanding and intellectual attributes. This chapter describes how the research was planned and designed to meet the aims of the study. It also describes how the research methods were designed and carried out as well as explaining how the results generated from these methods were analysed. The strengths and weaknesses of the data collection instruments are discussed. The constraints of the data collection are also addressed including the validity and reliability of the data collection tools and data analysis.

After the review of the related literature (Chapter 2) and the introduction of the context of the teaching approach investigated in this research study (Chapter 3), it seems appropriate to re-present the research questions at the beginning of this methodology chapter.

1) What level of knowledge, understanding and intellectual attributes do beginning undergraduate chemistry students have in relation to the Macromolecules course's content?
2) How are students' levels of knowledge, understanding and intellectual attributes influenced by the independent learning approach?
3) What are the students' views and experiences of independent learning?

In the literature review (*see* Section 2.8), it was concluded that the vast majority of the literature that show the benefits of independent learning are from complex teaching approaches which makes it hard to attribute all the mentioned benefits to independent learning itself. This research study investigates the impacts of a teaching approach which does not include any lectures and primarily relies on students' independent learning. In order to measure the impact of this teaching approach on students' knowledge, understanding and intellectual attributes, first of all a baseline of these measures needed to be set. Having established a baseline, the next objective was to determine the ways in which students' learning was influenced by the independent learning strategy used in the Macromolecules course. Finally, another significant conclusion from the reviewed literature was that little research is available about students' and lecturers' views of independent learning. In an attempt to fill the identified gap in the literature and to gather information which then could be used to improve the practice of independent learning approaches, students' and lecturers' views and experience of the approach are investigated.

4.1 Research Design

An appropriate research design arises from the need to draw conclusions and/or generalizations from research findings. Trochim (2006) described a research design as:

the glue that holds the research project together. A design is used to structure the research, to show how . . . the samples or groups, measures, treatments or programs, and methods of assignment work together to try to address the central research questions. (pp.124-125)

As outlined in Chapter 1, the first hypothesis of this research study is that the independent learning approaches can enhance the learning of specific ideas in Chemistry and contribute to some intellectual attributes of students at university level. In order to investigate the part that is related to the learning of chemical ideas, it was necessary to employ a tool which measures students' knowledge and understanding.

Two of the main criticisms of educational research are that it fails to use rigorous scientific methods (National Research Council, 2002) and that research in education may be alienated from real-life practice (Lagemann & Shulman, 1999). Both of these criticisms may be related to the problem of controlling the variables which can possibly have an impact on the results achieved in learning environments. It emerges from the literature that various educational researchers have oscillated in their research designs between two extremes. On the one hand, some have ended up being accused of employing non-scientific research designs in their research (the positivist argument), whilst on the other hand, others have been accused of keeping too many variables controlled in a manner that decontextualizes the learning environments (the anti-positivist argument). The aim of this current research study was to use a research design that would allow being as balanced as possible between those two extremes. Moreover, another important point is that this research is a study of a singularity; it is a study of a particular event. A study of a singularity includes experiment, non-random survey and case study. If we consider appropriate experimental designs, it becomes very clear that the main intention is not to explain situations but to depict them as more like an input-output statement. For example, if an experiment is conducted in which students are separated in two groups and one is taught in one particular way and the other is taught in a different way, and then they are both subjected to the same measurement, the result simply concludes the difference between the methods. However, in a case study, the essential feature is that sufficient data are collected for the researcher to be able to explore salient features of the case and to interpret what is observed in an objective manner. Furthermore, this study investigates aspects of a teaching approach in its natural context, and the one essential feature of case studies is that they are conducted mainly in their natural context. Drawing from those conclusions, the most appropriate research design for this current research study was therefore deemed to be a case study design.

4.1.1 Case Study Research

It has been discussed in the literature that despite the fact that there have been many references to case studies and case study design has been employed by many researchers; the majority of those studies have failed to provide a clear description of a case study. As Lincoln and Guba (1985) stated, whilst the literature is replete with references to case studies and with examples of case study reports, there seems to be little agreement about what a case study is. Some attempts at defining a case study will be given later in this section.

The relative use of case studies in educational settings, compared with other disciplines, has usually been seen as more immature due to its relatively recent introduction and the lack of understanding in educational settings compared with other disciplines. In the past, case studies have been used in the disciplines of sociology, anthropology, history and psychology and the professions of law and medicine, which have developed procedures for establishing the validity of case study, but its specific relevance to education has not been explored to the same degree (Simons, 1980). However, more recent research studies have shown that case study is frequently used in many social science disciplines including education (Verschuren, 2003).

Despite the fact that it is referred to as being used frequently in education by some scholars, case study was claimed to be undervalued in education by others (Ragin & Becker, 1994; Stake, 1995). This undervaluation may stem from a number of factors. Although a discussion of these is outside the scope of this research study, there is certainly room to observe that with a quite naïve intention, the lack of use of case studies in educational settings may be related to the increasing impact of positivism on educational research. The big impact of positivism on epistemology in educational research may lead to a shift towards more nomothetic rather than idiographic research methodologies.

One of the two most fervent recent promoters of case study is Yin (Tight, 2010). Yin (1994) described a case study as an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident. Whilst Yin (1994) emphasised the real-life context of case studies, Sturman (1994) pointed out that the techniques used in the investigation of a case study can be varied, and might include both qualitative and quantitative approaches, and that the distinguishing feature of case study is the belief that human systems develop a characteristic wholeness or integrity and are not simply a loose collection of traits. As a consequence of this belief, he claimed that in case study researches, in order to understand a case, to explain why things happen as they do, and to generalise or predict from a single example requires an in-depth investigation of the interdependencies of the parts and the patterns that emerge (Sturman, 1994). In the light of that, in this current research study the context of the research has been investigated deeply and a chapter of this thesis is devoted to disclosing the case as much as possible (*see* Chapter 3).

4.1.2 Advantages and Academic Criticism of Case Studies

Case study designs, as every other research design, have their own limitations and merits. So rather than strive to devise the one perfect research design for an educational setting, it seems a better approach to argue the relative perfection of each study design in each research study separately. As has already been explained, the case study design was deemed the best option for the methodology of this current research study (Section 4.1.1). In this section, the merits and limitations of the case study design will be discussed.

There is a quite comprehensive body of research about case study designs and the use of them in social science settings. Drawing a summary from those studies, one of the advantages cited for case study research is its uniqueness, its capacity for understanding complexity in particular contexts. And a corresponding disadvantage of case study is usually cited as problems related to generalizability from one single case. Such a conclusion creates a polarity and the majority of researchers in the social sciences find themselves defending one or other of these two polar points. However, this paradoxical structure of case study is seen by some as the whole point of case study, as Simons (1996) argued;

Paradox for me is the point of case study. Living with paradox is crucial to understanding. The tension between the study of the unique and the need to generalise is necessary to reveal both the universal and the unity of that understanding. To live with ambiguity, to challenge certainty, to creatively encounter, is to arrive eventually, at 'seeing' anew. (p. 1)

It could possibly be argued, in the light of Simons's comments about the paradoxical structure of case study, that some points suggested as disadvantages of case study may actually turn out to be advantages. Even though drawing too much attention to interpretation may be a mistake, invoking the privilege and responsibility of interpretation in case study emerges as a strong point of case study design.

The potential advantages of case study were listed by Adelman *et al.* (1980) in their broad research on case study:

a) Case study data, paradoxically, are 'strong in reality' but difficult to organise. In contrast, other research data are often 'weak in reality' but susceptible to ready organisation.

b) Case studies allow generalisations either about an instance or from an instance to a class. Their peculiar strength lies in their attention to the subtlety and complexity of the case in its own right.

c) Case studies recognise the complexity and 'embeddedness' of social truths. By carefully attending to social situations, case studies can represent something of the discrepancies or conflicts between the viewpoints held by participants. The best case studies are capable of offering some support to alternative interpretations.

d) Case studies, considered as products, may form an archive of descriptive material sufficiently rich to admit subsequent reinterpretation.

e) Case studies are ‘a step to action’. They begin in a world of action and contribute to it. Their insights may be directly interpreted and put to use.

f) Case studies present research or evaluation data in a more publicly accessible form than other kinds of research report, although this virtue is to some extent bought at the expense of their length.

On the other side of the coin, the case study design has been criticized harshly by some academics. Some of these arguments are that case studies do not allow rigorous, scientific generalizations, that they usually take too long to undertake and end up very long, and that it is almost impossible to read all the appropriate documents. Others have blamed case study writers usually for emphasizing the ‘instance’, the ‘particularity’ and the ‘uniqueness’ of their research, hence distinguishing their enterprise as far different from others. Moreover, it was claimed by Atkinson and Delamont (1985) in their critique of case study that this distinguishing characteristic might result in denial of the theory and methods. They asserted that if studies are not explicitly developed into more general frameworks, then they will be doomed to remain isolated, one-off affairs, with no sense of cumulative knowledge or developing theoretical insight. In general, the lack of generalizability of the findings appears to be the most significant critique. It has been argued by several researchers that generalizability is an expected feature of both the study of samples and the study of cases (Cohen & Manion, 1980; Stenhouse, 1980). Even though many researchers support the idea of generalization in educational research, the scarcity of generalizations is crystal clear. For instance, Maccoby and Jacklin (1974) reviewed 1400 studies of gender issues in the education field. Their comprehensive research was able to identify only four statements about sex differences in the performance and behaviour of children and young people, which they considered to be “fairly well established”. Even the results of those generalizations are so close that they could easily lead to misinformation. The fluctuation could result in exactly the opposite of generalization in the small classroom environment. In this sense, none of those generalizations is useful for teachers in their applications. Hence, some researchers have challenged the idea of generalization in educational settings.

Looking at the literature on educational research, it might be concluded that many researchers have been criticized harshly for their methods and their results. However, in educational contexts there are too many variables to be controlled and perhaps some of them are actually impossible to control. The number of variables is so high that even some obviously significant variables can remain uncontrolled in educational research. Furthermore, it should not be forgotten that human subjects are autonomous and they play a large role in their unpredictable impact on many research results. The possibility of interpreting open generalizations from human subjects is considerably low, if not impossible, compared with experimental research using material subjects from laboratory benches. Bearing these issues in mind, even experiments conducted successfully seem to provide results which are only valid for a specific group of people under specific conditions and it is difficult to draw conclusions that will apply in general. Despite the lack of generalizability in educational research, the body of research in education allows practitioners in the domain to acquire sufficient information for use, interpretation, improvement and understanding of learning and teaching activities. It also inspires them to create and apply new methods as well as assuming possible outcomes of their activities.

While the concept of generalizability is under discussion for educational research, it is relevant to consider the suggestion of Bassey (1981) who, in his comprehensive review of research into single events, introduced the concept of the "relatability" of research. He argued that the relatability of research, especially in the domain of pedagogic research even if not in all educational research, may be more meritorious than generalisability of research. Bassey (1981) contended '*that the study of single events is a more profitable form of research (judged by the criterion of usefulness to teachers) than searches for generalisations',* and suggested *'that the merit of study of single events lies not in the extent to which it can be generalised, but in the extent to which a teacher reading it can relate it to his own teaching'* (p. 73).

He claimed that educational researchers should eschew the pursuit of generalizations unless their potential usefulness is apparent. It seems that teaching practice could be improved significantly with the help of more relatable research in education. Misleading generalization attempts might harm teaching practice and should be avoided. Bassey (1981) suggested that assessment of case studies should not focus on their generalizability but should rather focus on relatability:

I submit that an important criterion for judging the merit of a case-study is the extent to which the details are sufficient and appropriate for a teacher working in a similar situation to relate his decision making to that described in the case-study. The relatability of a case-study is more important than its generalizability. (p. 85)

4.1.3 Categorisation of Case Studies

Case study has been categorised by various researchers mainly depending on either the aims of the research or the methodology employed. Stenhouse (1985) identified four different styles of case study: evaluative, action research, ethnographic and educational. He defined ethnographic case study as research based on cultural or social anthropology which emphasizes the roles of the actors in the case rather than their direct practical needs; evaluative case studies as studies that intend to provide information to educational actors or decision makers to judge the worth of policies, programmes, approaches or institutions; educational case study as research which is not concerned with policy or evaluative judgement but rather with the understanding of the educational actions; and case study in action as the categorization of cases that are under development which can lead to the revision and refinement of the action. This current research study can be considered as an educational case study according to the categorisation of Stenhouse.

On the other hand, Yin (1993) separated case studies into three different groups: exploratory, explanatory and descriptive case studies. In his categorisation, Yin focused on the aims of case studies rather than their results or methodologies. Exploratory case studies aiming to explore singular actions are relatively new and are the least assessed in educational settings. Exploratory case studies seek to reveal the advantages and drawbacks of relatively less-known singular actions and usually contribute to the literature by evaluating those actions that might have potential to be applied on bigger scales. Explanatory case studies aim to give detailed reports to explain single cases in educational settings: they usually include the evaluation of singular cases in terms of those actions' success at satisfying their overall goals. Explanatory case studies make connections between actions in educational settings and their impacts on education. Descriptive case studies are the broadest category of case studies in Yin's categorisation as they usually do not have particular assessment or evaluation aims; they are intended instead to give objective descriptions of actions in educational settings. Descriptive case studies usually avoid straightforward conclusions and instead simply describe circumstances and leave interpretation to the reader. Considering the fact that this current research study evaluates a new teaching approach which aims to promote independent learners' success at achieving their overall goals, it would best fit in the explanatory case studies category of Yin.

Stake (1995) differentiated two types of case study: intrinsic case study and instrumental case study. He separated case studies according to whether they are part of a continuous study to gather more and richer data about singular actions with the aim of establishing theories, or are one-shot research studies which are intended to investigate one particular single action in an educational setting, at a particular time in a specific environment. Instrumental case studies are continuous case studies which attempt to establish theories on an issue and intrinsic case studies are used to probe one specific case in detail. As the aim of this current research study is to contribute to independent learning theory and practice in education, it would fit in the instrumental case studies category of Stake.

Bassey (2000), in his comprehensive book on case study research in educational settings, distinguished three different types of case study. First, theory-seeking and theory-testing case studies, which focus on the issue rather than the case and attempt to contribute to the development of educational practice and policy. This category of case study can be related to Stake's instrumental case study. Second, story-telling and picture-drawing case studies, which are descriptions of educational events, projects, systems or programmes intended to illuminate a theory. This category of case study can be related to Stake's intrinsic case study and Yin's descriptive case study. Third, Bassey proposed evaluative case studies, which investigate the worthwhileness of an educational action. This type of case study is not necessarily interested in contributing to a theory, which makes it different from the other two groups of case studies. Although it would be difficult to find a tailored category for each specific case study, the categorisations discussed briefly above cover the majority of the research studies described in the literature. For this current research study, considering that it is a significant attempt to contribute to the development of the educational theory, practice and policy of the discovery instruction approach and is an effort to find a way of communicating the research findings to those who might use them, it is appropriate to classify it in Bassey's theory-seeking and theory-testing case studies category.

4.2 Methods used in the Investigation

Case study is a generic term for the investigation of an individual, group or phenomenon. As case study covers a broad range of investigations, the techniques employed in those investigations can vary widely. Case study can include both qualitative and quantitative approaches, but in educational settings qualitative approaches are often preferred over quantitative approaches. The reason behind this preference may be that the usual sample of educational research is extremely complex human systems. It has been strongly argued in the literature that rich and varied data collection is the key point of educational research (Brown, 1992). She claimed that clinical interviews, observations and teachers' notes should be employed in research as well as pre-test and post-test designs. In the light of this, in this current research study, in addition to pre-test and post-test, student questionnaires and interviews, lecturer interviews, teachers' course notes, informal discussions with students and lecturers, document analysis of course leader's published papers and the recording of the introductory lecture are taken into account to help with the interpretation of the results.

As was explained briefly in Chapter 1, the first and second research questions of this study investigate the impact of an instruction approach which aims to promote independent learning on students' knowledge of and understanding about chemical ideas and their intellectual attributes. To gather rich and meaningful data, pre- and post-tests were employed with 176 students. In order to identify potential misunderstandings by the students, diagnostic questions were devised and used as items in the tests.

In addition, two types of data collection were employed to gather data on students' and lecturers' views and experiences of the teaching approach. First, to generate data about the students' preferences of Chemistry courses and the ways that these courses have been instructed, a descriptive questionnaire was administered. Following the descriptive questionnaire, in order to specify the investigation on independent learning and gather detailed views of students, interviews were held with 24 students. The descriptive questionnaires were designed to collect data about the students' views on Chemistry courses and their instruction methods in the department, and the interviews were intended to explore students' views and experience of the particular teaching approach which aims to promote independent learning applied in the Macromolecules course. In total, six personal and six group (each consisting of three people) interviews were carried out. So, twenty-four students were interviewed. This section discusses the purpose of the research methods that were employed to address the research questions. Table 4.1 shows the research questions, data sources and applied methods used to collect data. Later in the section, the methods used in this research study will be explained.

Research Questions	Research Methods Used for Data Collection	Research Technique	Data Source
1) What level of knowledge, understanding and intellectual attributes do beginning undergraduate Chemistry students have in relation to the Macromolecules course's content?	Tests with Diagnostic Questions, Document Analysis	Pre-test / Post-test Design	176 first-year undergraduate Chemistry students (entire cohort) For Document Analysis: The course booklet
2) How are students' levels of knowledge, understanding and intellectual attributes influenced by the independent learning approach?	Tests with Diagnostic Questions, Document Analysis	Pre-test / Post-test Design	176 first-year undergraduate Chemistry students (entire cohort) For Document Analysis: The course booklet
3) What are the students' views and experiences of the independent learning?	Descriptive Questionnaire, Standardised Personal and Group Interviews, Document Analysis	Post Intervention Data Collection	For Questionnaire: 176 first-year undergraduate Chemistry students For Interviews: 24 students, 3 Lecturers For Document Analysis: The course booklet A journal article, recording of the introductory lecture

Table 4. 1: Research questions, Data sources and Applied Methods

4.2.1 Pre- and Post-Test Designs

In the literature, it is often clearly argued that association does not mean causation. However, possibly the most informative results can be collected by using before-and-after designs (also referred to as pre-test and post-test designs). It can be argued that controlled and uncontrolled variables in pre-test/post-test designs can create fewer problems than other design methods as the control group is ‘exactly the same’ as the experiment group. This can in theory lead researchers to draw more sensible conclusions about the research as it seems that the effects of experimental variables on the dependent variable are isolated. Nonetheless, it can also be argued that nothing stays exactly the same. Some of the changes may possibly occur not because of the impact of an experimental variable that is being investigated but as a result of other unexpected variables.

The simplest description of the pre-test/post-test design is that a set of measurements is collected from a sample of respondents before they are subjected to an experimental variable, and then after the intervention the measurement is repeated. Comparison between the pre-test and the post-test results provides information about the impact of the experimental variable.

On the other hand, a very common criticism of the pre-test/post-test design is the will of the sample. For instance, to measure the impact of a teaching intervention, first the base-line before the intervention is gauged and then the impact of the experimental variable from those of the sample who wish to participate in the post-test measurement is measured. It can be argued that those who are willing to participate in the post-test measurement are the people who already have an interest in the intervention. This situation could easily put the validity of the post-test measurement in doubt. In order to eliminate this disadvantage of the pre-test/post-test design, in this current research study, attendance at the pre-test and post-test measurements was strongly suggested to the students; however participation was not compulsory for ethical reasons (*see* section 4.3). Although it would be unrealistic to claim that the only change that has been monitored is due to the impact of the experimental variable, this precaution is nevertheless an important attempt to improve the validity of the results.

4.2.2 Preparation and Administration of the Diagnostic Questions

Designing tests with diagnostic questions requires planning, reading and exploratory pilot work in advance. Any specification of the tests should be related to and in accordance with the overall research aims. The next section will explain the reasons behind the pre-test and post-tests specifications that were chosen for the current study.

First, it is well known that there are many methods of data collection in educational research and that each of them has its own strengths and weaknesses. As explained in the previous section, in order to answer first two research questions of this study, pre-test and post-tests were used. The pre-test and post-tests were self-administered. The main reason behind this choice was to ensure a high response rate. Another advantage of self-administered tests is that it allows personal contact so that the possibility of misunderstandings is low, and the aims and objectives of the research project can be explained to respondents in person if it is necessary. In terms of the approach to the respondents, the strategies that were employed were advance warning (all the students were informed that they would be asked to participate in the research project several weeks before the project was launched), confidentiality (they were informed that all the data collected would be treated as confidential) and degree of interest (all the students were informed that their contribution might play a role in shaping the teaching approach of the course in the future). Pre-tests were given to students at the end of the introductory lecture in the presence of the researcher and the course leader. Every student was given either a green or a yellow coloured test with a coded number on it. Numbers were from 1 to 100. Students were asked to take a note of their colour and their number on the Macromolecules course independent learning package since they would be asked to write their number on their post-tests. Post-tests were given to students at the end of their tutorials, in which students received feedback on their independent investigation, in the presence of the researcher and the lecturers who delivered the tutorials. Students were asked to take the same coloured paper that they had completed in the pre-test and they were asked to write their number on the post-test. By this means, some sense of confidence was provided that all students did the same test as a retest.

The tests comprised three question courses: students' knowledge, their understanding of particular ideas, and their intellectual attributes (*see* Section 4.2.4). For establishing the order of the questions in the tests, the 'funnel approach' was used (Oppenheim, 1992). With the funnel approach, the questions start with a broader approach to the topic and then become more and more specialised. For that reason, the first questions were connected with general applications of macromolecules but the later questions were more specialised on the concepts related to macromolecules. The reason for picking the funnel approach was to increase the possibility of students taking an initiative to start doing the tests. Finally, all the diagnostic questions were open-ended. One of the goals of this research study is to reveal possible misunderstandings of university students about polymers. In order to collect rich and spontaneous responses, open-ended questions were chosen.

4.2.3 Devising Diagnostic Questions

One of the most important requirements of a research project is to create a reliable and valid research instrument which will be used for data collection. Bearing this in mind, the creation of the diagnostic questions for this current research study took quite a long time. The content, wording and organisation of the questions underwent several revisions. In this section, the key points of this long and complex process will be described. Before considering the content of each question separately, the common points of all the questions will be discussed.

First, there are some important issues which should be taken into consideration when creating effective diagnostic questions. These significant points were obtained from the analysis of the literature related to studies which had involved preparing diagnostic questions in science education, particularly in Chemistry education.

To start with, the questions must be sensible and also related to the prior knowledge that students had gained during their A-level Chemistry courses. The aim of this current study is to explore the differences which might possibly occur because of the experiment variable, so the base from which differences might emerge must be investigated. The aim was to monitor the possible differences in students' knowledge, understanding and intellectual attribute levels. To keep the level of questions too low or too high could hamper the monitoring of all the differences. The difficulty of the questions had to achieve a very sensitive balance, neither too hard to answer nor too easy so as to be boring. To achieve this balance, the appropriateness of questions was the key point, hence diagnostic questions were designed using a ‘Delphi approach’ (Clayton, 1997). According to Dakey and Helmer (1963) the Delphi approach may be defined as a method used to obtain the most reliable consensus of opinion of a group of experts. For this purpose, an academic from chemistry education who was the Director of the Salters’ Advanced Chemistry course which is a two-year, pre-university course for twelve- to eighteen-year-old high-school students, and two chemistry professors who specialise in Organic Chemistry were contacted. These academics had many years of experience in teaching Chemistry at both secondary and tertiary levels. Before piloting the questions, every question that had been prepared was checked and commented on by them. Discussions were held not only regarding the context of the diagnostic questions, but also the difficulty level, the clarity, the thought-provoking features of questions, any similarities/differences of the questions compared with exam questions, and practical features of the questionnaire such as time management, paper, print qualities, colours and the space available for answers.

An important concern raised by the academics was that the questions had to enquire into knowledge of one specific topic in Chemistry. Chemistry has many sub-branches, such as Organic Chemistry, Inorganic Chemistry, Analytical Chemistry and Physical Chemistry, and many of the concepts in these sub-branches are related to each other, so it was highly possible to create questions which required more information than was included in the course objectives. In this specific study, the topic was Polymer Chemistry, so the researcher tried to focus only on the Organic Chemistry related topics, and the chemical substances or reactions used in the questions were kept as simple as possible to ensure that they were familiar to every student, rather than very particular subject-specific reactions. Before the administration of the pilot study, the appropriateness of each of the diagnostic questions was approved by the academic advisors.

4.2.4 Aims and Contexts of the Diagnostic Questions

In this section, the diagnostic questions which were devised will be briefly examined. The questions will be categorised according to their aims.

4.2.4.1 Questions aiming to measure the impact on students' knowledge acquisition

The *Kevlar's Strength, Recycling*, *PIC* and *Functional Group* questions were designed to measure any impact of the Macromolecules course on students' knowledge acquisition.

In the *Kevlar's Strength* question, the students were asked to give the names of the intermolecular bonds that the Kevlar polymer has in its chemical structure. Kevlar's structure was covered in the content of the independent learning workbook.

Especially for the non-chemists in society, plastics and recycling are probably the most familiar aspects of Polymer Chemistry. In view of the wide use of those words, the researcher attempted to determine what the students already knew about those supposedly well-known chemical ideas. Not only in Chemistry but also in environmental education and in citizenship education the importance of recycling is being emphasized widely. The significance of recycling is also covered in the A-level Chemistry syllabus as a specific topic. In addition, recycling is a common activity throughout society as a whole. However, the question is why people do recycle. So asking the students to explain the importance of recycling allowed their views, with their possible misunderstandings, to be revealed.

Another question related to the recycling process was about plastic identification codes (PICs). It goes without saying that students are expected to use the knowledge that they gather during their education. PICs were introduced by the Society of the Plastics Industry in order to create a classification system for different types of polymers and that helps recycling companies to separate different types of plastics for reprocessing. To investigate students' knowledge of PICs, it was considered useful to ask them to discuss their acquisition of Chemistry knowledge which they use in their everyday lives.

Knowledge about functional groups is fundamental particularly to Organic Chemistry and Polymer Chemistry. Without sufficient knowledge about functional groups, it would be impossible to identify polymers and to assess their functions. So the students were asked to identify the functional groups of two specific polymers which are commonly used in medical science. Knowledge about recycling, PICs and functional groups were not covered in the independent learning workbook, but they were given as independent investigation topics.

4.2.4.2 Questions aiming to measure the impact on students' understanding of chemical ideas

The *Isomerisation*, *Mechanical Strength*, *Branching*, *Biodegradability*, *Chelate*, *Fashion*, *Polarity* and *Contact Lenses* questions were devised to measure any impact of the Macromolecules course on the students' understanding of the chemical ideas.

Not only in Polymer Chemistry but also in Organic and Inorganic Chemistry, cis-trans isomerism plays an essential role in deciding the properties of chemical materials. Cis-trans isomerism can be simply described as a form of stereoisomerism describing the orientation of functional groups within a molecule. Natural and synthetic rubbers are cis- and trans-isomers of the same polymer called polyisoprene. To measure the students' understanding of geometric isomerism, they were asked to compare the properties of two isomers of the same polymer.

There is no doubt that in the literature on Polymer Chemistry and in the Polymer Chemistry curriculum, there is considerable focus on intermolecular forces and hydrogen bonding is an essential concept for the understanding of Polymer Chemistry. In the *Mechanical Strength* question, students were asked to compare the physical strength of a PCL polymer and a PCL/PVPA mixed polymer, which measured students' understanding of intermolecular forces in polymers.

The increasing use of polymers to replace or supplement more traditional materials such as wood, ceramics, natural fibres and metals stimulates the search for more versatile polymeric structures in order to cover a wide range of properties. *Branching* in polymers has a great impact on their features, hence their use in industry. As it has such significant importance in industry, the structure of polymers takes up a large part of the polymers topic in the curriculum. Therefore, a fundamental knowledge of structure-property relationships is required. Bearing in mind the importance of the structure-property relationships in Polymer Chemistry, the students were asked to compare the tensile strength and resilience of two polymers depending on their different branched structures.

Biodegradability and *biocompatibility* are particularly important in the medical use of polymers. In order to investigate students' understanding of these two concepts, a question was devised which was contextualised with a very popular area of Chemistry, medical sciences. The medical science context had been used widely by the previous year's students in their projects for the Macromolecules course, so the respondents were asked to state what makes a polymer biodegradable and biocompatible.

It is frequently stated that tertiary-level education especially is the education level which is highly related to current research and that current research should never be isolated from university students. To ensure this, many researchers and lecturers stress that university students should be informed about recent research. In the *Chelate* question, the students were asked to use their knowledge about chelate forms in a medical application context.

An understanding of polarity is essential for many sub-domains of Chemistry, including Polymer Chemistry. Because electronegativity and polarity are the main concepts behind the bond structure and the dispersion of atoms in a space, those two concepts play a main role in deciding many properties of materials, including polymers. The *Polarity* question focused on the polarity differences between different polymers and the impact of these differences on the properties of polymers, and asked students to compare the solubility of two polymers. *Fashion* and *Contact Lenses* are two popular contexts of the Macromolecules course's content. The high level of interest among the previous year's students in these areas also triggered the idea of adding questions about these two contexts. In these questions, students' understanding of polarity in polymer structures is investigated.

4.2.4.3 Questions aiming to measure the impact on ability of scientific reasoning

The *Combustion* and *Wettability* questions were devised to measure any impact of the Macromolecules course on students' scientific reasoning.

Possibly some common misunderstandings of students stem from the fact that some students see their school science as completely detached from their everyday life experiences. This delusion causes students to inhabit two different worlds in which they think in different ways. For instance, when students are asked to draw the chemical structure of polyethylene, many of them seem to have no problem with that. However, when they have been asked to draw the chemical structure of the plastic bags which they use to carry their shopping home, it seems that this is a bigger challenge for them despite the fact that they know that the bags are made of polyethylene. As mentioned in the literature review, scientific reasoning requires some data generated through the sorts of interactions with the real world assumed in the predictions derived from the model which requires an ability to transfer from the real world to the model's world appropriately. In this question, the data generated through the sorts of interactions with the real world is the students' observations of the combustion of HDPE and LDPE polymers. Predictions derived from the model are the end products of combustion reactions of these polymers, which are CO_2 and H_2O. It is argued here that the students who gave the correct answer to this question had better ability to transfer from the real world to the model's world and *vice versa*; hence they had better scientific reasoning.

Similarly, in the wettability question the students were asked to explain the wetting phenomenon and their scientific reasoning attributes were judged from their explanations. It was expected that those students who had better scientific reasoning would be able to think about the chemical structure of PVPA and would generate the scientifically correct answer for the question. On the other hand, students who were less successful at scientific reasoning would think about their personal experiences of the wetting of materials but they would not be able to transfer from the real world to the model's world or *vice versa*.

4.2.4.4 Questions aiming to measure the impact on self-assessment abilities

The *Calculation* question was included to measure the impact of the Macromolecules course on students' self-assessment ability.

The item attempted to investigate students' metacognitive ability of self-assessment before and after the instruction strategy investigated. In order to achieve this, the students were given a calculation in the Polymer Chemistry context. All the required formulas and values were given in the question except for some unit conversions. If a student were to omit the unit conversion, s/he would obtain an absurd result, and it was expected that this would make him/her go back and check the calculations again. It is hypothesized that the students who had better self-assessment ability would attempt to check their answers and change them since an absurd result had occurred.

4.2.4.5 Questions aiming to measure the impact on ability to generate creative solutions

The *Disposal of Kevlar* question was designed to measure any improvement in students' creativity in generating solutions to chemistry-related problems. Creativity is one of the expected features of modern chemists. The question asked students to generate a creative solution to a Polymer Chemistry-related problem. The differences in their responses to this question will be used to assess any differences in their ability to generate creative solutions.

4.2.5 Other Data Sources

In addition to the pre-test and post-test, data related to students' and lecturers' views were also collected. There are numerous reasons behind the decision to collect data from other sources. First, as was stated in the literature review, little research is available about students' and lecturers' views of the teaching approaches which aim to promote independent learning. This is a gap in the literature which this current study aims to contribute to filling. Second, some of the learning objectives of the course investigated include objectives relating to students' intellectual attributes (*see*

Table 3.1). The course's impact on these intellectual attributes was measured by the pre-test and post-test; however in order to create an opportunity for the triangulation of the data collected in the pre-tests and post-tests, students were interviewed about the impact of the course on their intellectual attributes. Third, in the literature it was claimed that the rationale behind the shift from a traditional teaching approach to independent learning has a significant impact on the independent learning approach's success (Salmon, 2002). Hence, the data related to the rationale behind the change of the teaching approach required additional data sources such as interviews with lecturers or document analysis. Fourth, in the literature on case studies, it has been strongly suggested that rich and varied data should be collected to enable better conclusions to be drawn (Brown, 1992). Varied data collection also makes the context of the case study clearer to the reader. In the following sections, the data sources and data collection methods, other than diagnostic questions, used in this research study will be explained.

4.2.6 Questionnaires on Students' Views

First, in order to gather data about the students' views of Chemistry courses and their instruction methods to compare with the Macromolecules course, a descriptive questionnaire was used. This section discusses the purposes of the descriptive questionnaire.

The main purpose of descriptive questionnaires is to show how many members or what proportion of a population has a particular opinion or characteristic, but not to explain or to prove any causal relationship between one variable and another. The purpose of such designs is fact finding or/and descriptive, but they are widely used in the social sciences for making predictions or more often to support other types of data collected. In this current study, the reason for using a descriptive questionnaire was to collect data on students' preferences of the independent learning course compared with the other courses which they took in the Department of Chemistry. A shortcoming of such research instruments is that they cannot answer 'why' questions. Even so, they are quite useful for collecting fast and broad data to be used to support data collected by other methods. The questionnaire is attached as Appendix 4.

In this research study, the descriptive questionnaire was employed to collect data on four different themes. First, it asked what features of Chemistry courses helped students to develop their understanding of chemical concepts. The main reason for including this question was to investigate whether students find any features of the independent learning approach (such as to be flexible in terms of time and place of study) particularly beneficial to the development of their understanding of chemical concepts. The second question explored what features of Chemistry courses make those courses particularly enjoyable to study. Similar to the first question, this question was designed to identify what features of the independent learning approach students found enjoyable.

The third and the fourth questions were ranking questions. They asked the students to give the names of three courses which they had taken during their first year of tertiary-level education. The intention was to probe whether the students considered the Macromolecules course, and hence indirectly its independent learning approach, as significant in terms of developing their understanding of chemical ideas or as particularly enjoyable. The rankings of the courses were expected to give a clear idea about their appreciation of the independent learning approach compared with other learning strategies which had been applied in other first-year courses. The third question asked the students to give the names of the three courses that had particularly helped them to improve their understanding of chemical ideas, and the final question asked them about the courses that they had particularly enjoyed studying.

4.2.6.1 Administration of the Questionnaire

Questionnaire forms were given to 176 students during their college tutorials about the Macromolecules course (during post-tests) and they were asked to complete and return them in their own time. Eventually, 167 students returned a completed questionnaire. For the process of analysis of the questionnaire, the content analysis approach, using open coding, was employed. Content analysis is a technique for making ‘inferences’ by ‘objectively’ and ‘systematically’ identifying specified characteristics of messages (Holsti, 1969, p. 14). For this purpose, a coding scheme was used in which each dimension of the data was represented by features of the lectures mentioned by the students. To do this, first the students’ responses were read and each feature mentioned by the students was added to the coding scheme such as demonstrations, solving example questions or independent learning. Then this coding scheme was used to code the data. Open coding was used as it is transparent, repeatable (that is, reliable) and highly flexible (Bryman, 2008).

4.2.7 Interviews

After questionnaires, in order to reveal students' views of the particular independent learning approach in more detail, interviews were held. There are a few reasons for using interviews as a data collection method. First, interview is a relatively richer method of data collection compared with other data collection methods, including questionnaires. The luxury of having face-to-face interaction with interviewees gives the opportunity of gaining a clearer sense of their perspective. Since an interview enables respondents to give prompt responses to open-ended questions, it is more likely that their answers will be sincere. Open-ended interview questions are very valuable in allowing respondents to say frankly what they think and to do so with richness and spontaneity. Another argument for this technique is that it is commonly considered to give higher validity to interview data. Because the interviewer actually sees and talks with the interviewee and usually reports responses verbatim, this increases the validity of the data compared with receiving responses by other methods.

Ensuring that the students felt totally free to express all their thoughts about the independent learning approach was essential in order to claim the reliability and validity of the responses to the interview questions. Especially considering that the respondents were enrolled Chemistry students who would continue their education in the same department for at least the next two years; it was quite natural and possible that they might feel uncomfortable about expressing their ideas openly and sincerely. One of the significant reasons for choosing face-to-face interviews was that the interviewer would have the opportunity of interaction with the students, and by using this method, the interviewer had the opportunity to introduce himself and explain his research study, which it is assumed would increase the students' understanding of the unbiased, subjective structure of the study. The students were reassured again that this particular education research study had no relationship with their department and that any information they provided would only be used by the researcher for independent research purposes. Before, during and after the interviews, the interviewer attempted to create a friendly environment to make the students feel as comfortable as possible.

4.2.7.1 Sampling for the Student Interviews

Sampling for the interviews was convenience sampling. In the data generated from the descriptive questionnaires, there were twelve students whose responses were coded with independent learning. That means that these twelve students either thought that the independent learning approach was particularly helpful for them to improve their knowledge of or understanding about chemical ideas or that they thought that it made studying Chemistry courses enjoyable. These twelve students were invited to an interview. In addition to these students, an e-mail was sent to the rest of the students from the course's enrolment list with an invitation to attend an interview about the course and twelve of them accepted to be interviewed. Hence, in total twenty-four students formed the sample for interviews.

Each student appears to have a different preference about the most comfortable environment for revealing personal opinions; whilst some prefer personal interviews, others prefer group interviews. In order to give an opportunity to choose the most comfortable interview technique for the students, these twenty-four students were asked whether they wanted to be interviewed individually or in a group interview. Six students preferred to be interviewed individually. The other eighteen students were interviewed in groups of three students, hence in total six group interviews were held. In the literature, the advantages of group interviews are argued as that they allow the exploration of the principal issues in a dynamic manner. This dynamic manner is related to the group interaction in challenging and probing the views and positions espoused by the individual members in a non-threatening environment (Osborne & Collins, 2001). The number of groups was six and previous research studies suggest that it is possible to reach data saturation even after three group interviews (Vaughan, Schumm & Siaguh, 1996). There is controversy in the literature about the ideal number of people in group interviews. The suggested numbers vary between three and twelve depending on the particular aims of the research. In this research study, the number of students in each group was kept at three in order to increase the contribution of each student during the group interviews.

4.2.7.2 Administration and Recording of the Student Interviews

Appointments were made with all of the students through their university e-mail addresses. Before the interviews, the interviewer had not met with any of the students. The students were invited to the research resources centre on the campus which has specially designed interview rooms with all the required equipment for interview recording. All the interviews were held in these specially designed interview rooms and they were video recorded with the students' consent.

By using a relaxed and friendly approach, the interviewees were put at their ease before, during and after the interviews. The confidentiality and the independence of the research study were explained clearly before the interviews began. Structured interviews were the format used for the investigation. There were two main reasons for this decision. First, the intention was to collect information about precisely the same issues from each student. Second, because of the researcher's lack of confidence to conduct an effective unstructured interview in a second language at the time when these data were collected, a structured interview was seen as a safer choice compared with unstructured interviews in which the interviewer can keep on asking spontaneous questions on pre-decided topics.

4.2.7.3 Student Interview Questions

The first interview question asked students to describe the differences between the teaching of the Macromolecules course and the teaching of other courses. The intention of this question was to see which features of the independent learning strategy were clearly observed by the student. Following that question, in order to investigate which of those features of the independent learning strategy were appreciated by the student and which of them were found distracting, the interviewer asked about the most-liked and the least-liked features of the teaching approach. Every question was followed by a 'why' or 'for what reason' follow-up question to probe the students' reasoning behind their answers.

Due to the fact that the learning objective of the Macromolecules course is to improve students' intellectual attributes, the next interview question asked the students whether they had developed any skills or not, and what made them think like this. For this specific question, the interviewer tried to generate students' thinking by asking them to give an example of a skill that they had subsequently used which they believed that they had developed during this course. The word 'skill' was used in interviews since it was found easy to understand by students.

Question four investigated the possible impact of the independent learning experience on students' learning practices by asking the students how their learning had been affected by the instruction method that they had experienced. The aim of this was to explore any possible impacts of the approach on students' learning activities, such as whether they tended to use different learning strategies more than they had done in the past, or whether they tended to spend more time searching for a new piece of information.

Question five was related to the students' experience of being an 'independent researcher' and of presenting their 'findings' as part of their assessment during the Macromolecules course. The main aim of this question was to investigate the sense of being independent among the students during the Macromolecules course. The interviewer attempted to analyse whether the students' opportunity to research their own interests had had any impact on their interest in Chemistry.

Another objective of the course investigated was related to time management. There was a danger of students getting stuck with their independent research, or not spending enough time on it as they did not receive guidance during the second part of the course. The interviewer wanted to have a sense with this question about how much time the students had spent on a four-credit course which should take approximately forty hours of work.

Since the independent learning approach was novel for the students, the interviewer wanted to probe whether their view of teaching had been affected by it, and question seven asked the students whether they now saw teaching at tertiary level as different from their opinion before they took the Macromolecules course.

In order to gather detailed information about the students' own experience of the independent learning approach, the next two interview questions asked them to describe the biggest challenges for them and what advice they would give to the next year's students. By asking this, the researcher hoped to collect data on the students' views of the drawbacks of the learning strategy.

The final interview question asked the students how representative their views were of the group as a whole. The data collected from the responses to this question were used to support the generalizability of the findings from the interviews to the entire cohort. The questions that were asked in the interview can be seen as Appendix 5.

4.2.7.4 Lecturer Interviews

There were three main reasons for interviewing the lecturers. First, in the literature it was claimed that the rationale behind the shift from a traditional teaching approach to independent learning has a significant impact on the success of the independent learning approach (Salmon, 2002). Hence, the data related to the rationale behind the change of the teaching approach required additional data sources such as interviews with lecturers or document analysis. Second, in the literature on case studies, it has been strongly suggested that rich and varied data collection is the key point in order to reveal the details of a case study and understand them better (Brown, 1992). Finally, lecturer interviews were used in an attempt to triangulate the data generated from the student interviews and questionnaires. As explained earlier, the student interviews and questionnaires were used to collect data about students' views and experiences of the course. To triangulate the data generated from the student interviews and questionnaires about their experiences of the Macromolecules course, an interview with the lecturer in which he could explain what he wants them to experience, and two interviews with two other lecturers in which they could talk about their views of the students' experiences were undertaken.

Sampling for the lecturer interviews was also convenience sampling. Seven lecturers were involved in the tutorials of the Macromolecules course. An invitation to attend an interview about the independent learning approach of the Macromolecules course was sent to all these lecturers and three of them, including the course leader, accepted this offer. Appointments were made with these lecturers through their university e-mail addresses. Due to the busy schedules of the three lecturers, the interviews were agreed to be held in the lecturers' rooms in their department. All the interviews were held in their rooms and they were audio recorded with the lecturers' consent.

The interviews were carried out during the two weeks after the course had been completed. Using a relatively formal approach, the confidentiality and the independence of the research study were explained clearly before the interviews began. Structured interviews were again the format used for the investigation for the previously mentioned reasons (*see* section 4.2.7.2). Each interview took approximately one hour. The questions that were asked in the lecturer interviews can be seen in Appendix 7.

4.2.7.5 Managing the Interview Recordings

As previously mentioned, all the student interviews were video recorded using digital video with sound technology and the lecturer interviews were audio recorded with a voice recorder. Later, the interviews were transcribed using the verbatim transcription approach. Verbatim transcription refers to the word-for-word reproduction of verbal data, where the written words are an exact replication of the recorded words (Poland, 1995). A combination of verbatim transcription and researcher notation of participants' non-verbal behaviour has been cited as being central to the reliability, validity and veracity of qualitative data collection (MacLean, Meyer & Estable, 2004; Seale & Silverman, 1997; Wengraf, 2001). The existence of verbatim transcripts is also beneficial in facilitating the development of an audit trail of data analysis by supervisors or independent people.

After the preparation of the transcript documents, these documents were uploaded to the NVivo programme. NVivo is intended to help users to organize and analyse non-numerical or unstructured data. The software allows users to classify, sort and arrange information, to examine relationships in the data, and to combine analysis with linking, shaping, searching and modelling. Using this software, the interviews were open coded which led to the development of a number of themes, namely novelty, appreciation of the independent learning, disapproval of the independent learning, contribution to skills, negative impact on learning, positive impact on learning, impact on interest, impact on studying activities, challenges and representativeness. The findings from the interviews will be presented in Chapter 7.

4.2.8 Document Analysis

Document analysis is the systematic analysis of a transcript of naturally occurring verbal material including conversations, written documents such as diaries or organization reports, books, written or taped responses to open-ended questions, media recordings, and verbal descriptions of observations (McTavish & Pirro, 1990). Traditionally, trained coders are used but serious validity, reliability and practical problems have led current researchers to utilize computer approaches which can possibly permit more systematic and reliable coding of themes and meanings in documents (Markoff, Shapiro & Weitman, 1975). In this current research study, three types of document were analysed. First, the course booklet prepared by the course leader was analysed in order to investigate the features of the booklet which aim to promote independent learning. These features were explained in Chapter 3 in detail (*see* Section 3.1.3). Second, an article by the course leader in which he described the required change in university-level Chemistry teaching referring to the individual learning approach of the Macromolecules course. Both of these documents were uploaded to the NVivo programme and analysed using open coding to draw conclusions about the aims of and motivations behind the independent learning approach investigated in this study. Finally, a recording of the introductory lecture to the Macromolecules course in which the course leader introduced the independent learning approach and explained the reasons behind the change in the teaching method of the course from the more traditional approach to the independent learning approach was transcribed verbatim and analysed.

4.3 Ethical Aspects of the Study

All research undertaken by students in the Department of Education should be conducted in a manner that complies with normal ethical guidelines for research on education. The university in which this research study was undertaken has ethical guidelines linked to the guidelines of the British Educational Research Association (BERA). For this current research study, the department’s ethical issues audit form was completed and it was signed by the supervisor and thesis advisory group’s members and the study was approved to go ahead. The department's ethical issues audit form is attached as Appendix 9. During the pre- and post-tests, it was explained to the students that their contribution was entirely voluntary and they were kindly asked to contribute to this research and answer the questions only if they wanted to do so. Similarly, all the interviewed students were informed prior to the interviews in a letter which explained the aim and structure of the research study. Students who understood that their contribution was entirely voluntary were kindly asked to put their initials to the letter if they still wanted to be interviewed for independent research purposes. The students were also informed about the anonymity and confidentiality of the data generated.

4.4 Polymer Chemistry in Education and the Diagnostic Questions in Contexts

Although in terms of the educational aspect there is a lack of literature, the importance of Polymer Chemistry teaching has occasionally been signified (Jefferson & Philips, 1999). It has been shown in the literature that those who learn Polymer Chemistry after gaining a job in the polymer industry struggle to understand the fundamental concepts of Polymer Chemistry (Wagener & Ford, 1984), so it was suggested that Polymer Chemistry should be part of the Chemistry curriculum. In the beginning, it was suggested in significant reports that Polymer Chemistry should be taught as part of other core courses such as Physical Chemistry (ACS Polymer Education Committee, 1985) or Inorganic Chemistry (ACS Polymer Education Committee, 1984). Recently, however, Polymer Chemistry has begun to be taught in many universities as a separate undergraduate course. Moreover, Polymer Chemistry is also part of the Chemistry curriculum in many secondary schools in the UK.

A recent study of the difficulties in the Polymer Chemistry domain revealed that the most 'problematic' concepts in Polymer Chemistry teaching are the concept of coefficient in the expression 'mol coefficient' in condensation polymerisation, the concept of coefficient in the kinetic equation of initiation and termination for radical polymerization, and the concept of kinetic chain length (Chen & Feng, 2011). However, the investigation of these concepts was impossible for this current research study as these concepts were not covered in the content of the Macromolecules course.

Considering the fact that the sample of this research study was beginning undergraduate Chemistry students, the A-level specifications also required attention in order to have an idea about the students' previous knowledge of polymers. In the investigated A-Level specifications, Polymer Chemistry has three sub-topics: addition polymers, condensation polymers and the biodegradability and disposal of polymers. Under these three themes, students are required to be able to draw the repeating unit of addition polymers from their monomers and *vice versa*, to have a basic idea about the dicarboxylic acids, diols, diamines, polyesters such as Terylene, and polyamides such as nylon 6,6 or Kevlar, to understand that there are biodegradable and non-biodegradable polymers, and to appreciate the advantages and disadvantages of different methods of the disposal and recycling of polymers (GCE AS and A Level Specification of Chemistry – AQA, AS exams 2009 onwards and A2 exams 2010 onwards). Students are also expected to comprehend factors affecting the properties of polymers, polymer chain length and the ability of polymer chains to slide over each other, as well as natural and synthetic polymers (AS/A Level GCE Specification of Chemistry – Salters, 2008).

Another important point is that each question was presented in a context that was related to possible interest areas of students. It has been shown in the comprehensive review of the literature that context-based/STS approaches can increase the interest of school-age students (Bennett *et al*., 2007). Similar results later echoed this for students at tertiary level (Garrison & Vaughan, 2008). To keep students' interest levels high, diagnostic questions were also presented in specific contexts. The contexts of the questions were decided after investigating the outcomes of the previous year's Macromolecules course. These outcomes were the video presentations and articles of the students about the findings from their research in the field. The topics of the presented materials that had been created by the previous year's cohort were the recycling process, polymers in medicine, polymers in fashion, polymers in aeromechanics, polymers in sports and polymers in building materials. So the contexts used for the diagnostic questions were the recycling process, fashion and fabrics, the bone grafting process and the pipe industry. Each word that was used in the questions was expected to be familiar to the students and any words that might have been problematic for the students were defined in the questions in order to prevent any misunderstandings stemming from unfamiliar words.

4.5 Pilot Study

In order to ensure the coherence of the questionnaire for the main research study, a well-organized pilot study had to be carried out. Although the main motivation of the pilot study in this current case was to assess the wording of the questions and their suitability for the beginning undergraduate Chemistry students, piloting the questionnaire helped to improve the design, application and order of the questions. The organisation of the pilot study, its application and some key points which emerged from it will be discussed next.

First, before the pilot study was undertaken, it is important to repeat here that all the questions were devised using a Delphi approach (*see* Section 4.2.3). A wide range of topics including wording, structure, coherence, suitability for sample students' level and chemical sensibility were discussed with professionals involved in the creation of the diagnostic questions. Prior to the piloting, a number of modifications had already been made to the diagnostic questions with the intention of improving them.

Following the modification process, the eighteen questions which had been created were printed. On the front page of the tests there was a preface which explained the main aims of the research in order to inform students about the fact that their contribution was completely voluntarily and to give an introduction to the research study which had given rise to the test. On the final page of the test, the students were asked to write their comments about the questions. In order to stimulate their thinking, some possible topics were suggested, such as the difficulty of questions, the clarity of questions, any thought-provoking features of questions, similarities/differences of the questions compared with exam questions, and practical features (*see* Appendix 6).

Since the entire cohort of first-year students were the target sample of the main study, the pilot study sample was picked from two UK universities which had the same entry requirements for their Chemistry departments and had a Polymer Chemistry course with similar learning objectives to those of the Macromolecules course. Prepared questions were sent to twenty-two undergraduate students, and twelve completed responses were received back, from eight males and four females, from four different nationalities, British, Turkish, Greek and Dutch. There was no time limitation for them to complete the tests and they were asked to write down their approximate time-span for completing it.

Informal discussions with the students who participated in the pilot work were also held in order to identify any problematic feature of the tests.

4.5.1 Results of the Pilot Study

The pilot questionnaire was sent to twenty-two students and twelve responses were received, a response rate of 55%. For posted questionnaires or in more recent researches studies e-mailed questionnaires, a response rate of 55% can be accepted as a success. The most likely reasons for the low response rate in the pilot study could be that the students found the tests far too long, that they were not obliged to complete the work, and that their work would not be assessed. As a result, the twelve collected tests were enough to draw useful conclusions which led to several modifications of the questionnaire. In this part, an examination of the answers received in the pilot work will be presented.

Recycling Process Questions

Many of the students gave some part of the right answer to these questions. However, the number of students who answered the question totally correctly was quite low. These answers indicated that the students had understood the questions correctly as they all gave answers on the right lines. Examples of answers to the recycling question are,

Resources for producing new plastics from raw materials are less plentiful than they used to be ...

Breaking down of waste plastics takes a lot of time and energy, not to mention landfill space – none of these resources are infinite ...

Production of new plastics is often very costly and not environmentally friendly either, with the need for solvents and energy etc ....

Examples of answers to the PIC question are

easy to decide which to use for a certain purpose ...

identification for recycling purposes ...

identification of ways to break down waste in landfill ...

Since these two questions seemed to meet expectations, they were both kept in the main tests without change.

Branching Question

The correct answer to the question was given correctly by almost all the students, although they failed to explain their reasoning for their answers. An example of the responses which is close to the correct explanation is

HDPE has scope for a lot of Van der Waals interactions along the chains. This will make the Polymer strong, resisting bending and impact. The possible interactions in LDPE are of shorter range and will therefore allow more pliability.

However, the scarcity of well-explained answers suggested that the students had problems with their understanding of the branching concept in polymers. One important issue which arose was related to the printing of the question, as some of the students commented that the molecular structures of the two polymers should have been given on the same page as it was quite awkward to go through the pages in order to see both of the polymers at the same time.

... it would be less time-consuming to answer if the HDPE and LDPE structures were on the same page.

Considering the issues raised, the question was kept unchanged for the main study but the printing of the question was rearranged so that the two structures appeared on the same page.

Combustion Reaction Question

This question created two answer streams. Approximately half of the students were able to answer the question completely correctly. The incorrect answers revealed some misunderstandings. One example from the first answer stream is

… mainly carbon dioxide and water, as these are pure hydrocarbons; a certain amount of soot (carbon) and carbon monoxide will also be produced if combustion is not quite complete. This will depend on the availability of oxygen.

Examples of the second stream of answers are

Just a black stuff really.

Burnt plastic, I am not sure about this one.

Fashion Question

This question yielded answers which varied in the amount of knowledge and detail included. Some students were confused over the idea of intermolecular bonds; some were able to identify the hydrogen bonds correctly but others could not. The numbers of correct answers and totally wrong answers were quite low, and the answers were fairly evenly divided between correct and incorrect answers. The variety of the answers suggested that this question could be effective at revealing variance in understanding. As the question was found by some students to be less coherent, two pictures of the polymers used in fabrics were added as a modification to this question. An example of the answers is

The breathable feature of Gore-tex stems from the structure of the Polymer as it has holes big enough for steam to pass through but too small for water molecules. That is not the case for nylon.

Natural and Synthetic Rubber Question

The natural and synthetic rubber question investigated students' ideas about the cis- and trans-isomer structures of Polymers. Even though many students were able to give the correct answer to this question, their reasoning seemed wrong. They seemed to struggle to comprehend the general features of cis- and trans-isomers of polymers. So this question was kept in the main study. The answers given were similar to this example:

The trans conformation allows for more sliding of Polymer chains past each other and will therefore be more flexible; the cis form will be more brittle as chains cannot slide past each other so easily when forces are applied.

Intermolecular Forces Questions

In the pilot study, the questions related to intermolecular forces received the most answers. All of the students answered all of the questions related to intermolecular forces. Although most of them were able to answer the questions correctly, some students gave wrong answers. Although many of the students were able to see that Kevlar has very strong intermolecular bonds, they generally failed to name those intermolecular forces. The same was the case for the hydrogen bonds – students were aware of the existence of the hydrogen bonds but they struggled to identify them in the structure of the polymers. So this question was kept in the main study. Some examples of the students' answers are

Hydrogen bonding and other intermolecular force.

More hydrogen bonding.

There are considerably more and stronger intermolecular interactions between the Polymer chains if PVPA is present, with more hydrogen bonds (although perhaps fewer Van der Waals interactions).

Functional Groups Question

The students were asked to show the functional groups of two different polymers. This question was answered by every student and it was very clear from their responses that the respondents comprehended some functional groups very well, but they were not able to identify other functional groups correctly. For example, whilst all of the students were able to show the carboxylic acid functional group, only two of them were able to detect the phosphoric acid functional group in the polymers. So it seemed necessary to keep this question in the main study. Examples of the most common answer to this question are

PCL: keto (C=O) and ether (-O-), as well as alkyl ...

PVPA: phosphate and carboxylic acid, as well as alkyl.

Biodegradability and Biocompatibility Questions

For these questions, the students again produced a range of answers. Although many of them were able to explain the biodegradability of polymers, they seemed to struggle in finding the right explanation for biocompatibility. An example of the answers which were close to the correct answer is

Both Polymers allow for hydrogen bonding; they have functional groups that are common in the human body and will probably not cause the immune system to react to them, and they can be broken down through hydrolysis although they probably need fairly drastic reaction conditions to achieve it. Not completely sure what the hydrolysis products might be, and what these might do to a human body if hydrolysis takes place.

Chelate Question

The question probing the students' understanding of chelates yielded a very wide range of mostly incorrect responses. This suggests that the students had very poor comprehension of chelate structure. Even though the concept is also covered in the A-level Chemistry curriculum, it seems that many students lacked an understanding of it. Generating a very wide range of answers allowed the researcher to investigate students' misunderstandings in different areas, so this question was kept in the main questionnaire. An example of the students' answers to this question is

Carbonyl oxygens from both phosphate and carboxylic acid groups would form dative bonds with the calcium, probably in an octahedral conformation.

Polarity Question

The questions on polarity were answered by an overwhelming majority of the students and all of the answers were in the right direction. That is a clear sign that the questions were well understood. On the other hand, some of the answers contained controversies, or they had right answers with wrong reasoning. Some students gave answers that were indicative of misunderstandings. So these questions were kept in the main study. An examples of a correct answer is

Neoprene is considerably polar, isoprene much less so; I would run the non-polar petrol through the polar neoprene so that it would flow without 'sticking' to the pipe wall, whilst I would run the polar brake fluid through the non-polar isoprene for the same reason.

An answer showing a clear sign of misunderstanding is

Neoprene has chloride which is quite electronegative, if there are electronegative atoms in a molecule that means that this molecule has to be polar ...

Types of Polymerisation and Types of Polymers Questions

In these two questions, the students were asked to identify polymerisation types and polymer types depending on the information given in the questions. These two items were not included in the main study for several reasons. First, they seemed to provide too much information to the students by giving all of the descriptions of types. Second, the preambles which were required for the questions were far too long for very short answers, so they were not time-efficient for the questionnaire. The third, and probably the most important reason, is that all of the students in the pilot study answered these two questions correctly. That is a clear sign that the questions would not enable to monitor possible differences between the pre-test and post-test results. Examples of the respondents' correct answers are

PCL: addition Polymerisation, PVPA: addition Polymerisation.

PCL: homoPolymer, PVPA: coPolymer.

Calculation Question

Students were asked to calculate the result of a chemical equation using a calculator. Most students failed to make the required unit conversion in order to obtain a sensible answer for the question. This question therefore seemed significant to add to the main study, as it would be useful to know the extent of that mistake in a large group. To increase the possibility of students realising their mistake and checking their answers to the question, it was modified and asked for explanations of the answers to be given along with the calculation. It was expected that as it would not make sense to explain the number found by an incorrect calculation, the students would go back and double-check their answers.

An example of the answers given to the question is,

$$E = h.f = h.\frac{c}{\lambda} = 6.62 \text{ x } 10^{-34} \text{ Js x } 3 \text{ x } 10^{8} \text{ m/s} / 3 \text{ x } 10^{-7}\text{m} = 6.62 \text{ x } 10^{-19} \text{ j}$$

$$328 \text{ kJ/mol} = 328\text{kj x } \frac{1\ mol}{6.02\ x\ 10\text{^}23} = 5.45 \text{ x } 10^{-22} \text{ kj/molecule}$$

4.5.2 Conclusions from the Pilot Study

After the pilot study, several conclusions were drawn. First, the difficulty level of the questions seemed appropriate for the students; the participants had been able to understand all of the questions, they were familiar with the terminology used and they seemed to understand what answers the questions required. Second, the test was far too long for students to answer in one go. The average time spent answering the eighteen questions was forty-five minutes. Two questions were removed after the pilot study as explained above, but even so it would still take approximately forty minutes to complete the sixteen remaining questions. After discussions with the course leader, the agreed time which it should take for the students to complete the test was twenty minutes. So it was decided to divide the test into two parts and to print each half on different coloured papers. It was expected that each test would take approximately twenty minutes after this division. Third, many of the questions generated quite a wide range of answers. This is an indication that the test was suitable for a research study designed to explore students' misunderstandings. Fourth, the students had been confused and asked for extra attention to be given to printing issues, such as if two polymer structures which students were asked to compare are printed on different pages, this can cause significant problems over the use of time and with students' visual convenience. Finally, it was found from the pilot study that the students expected to see accuracy and consistency in the way that the chemical structures were drawn and their names written. For the pilot study, many of the structures used in the tests were taken from different sources, so the relative lengths and widths of the bonds in the chemical structures, or the font in which their names were written, were varied. This created some confusion and also presented the test in a less professional way, leading it to be less appreciated than it should have been. It was therefore decided to draw all the chemical structures with careful attention given to the relative length and width of the bonds in them and to the font in which their names were written. All of the structures were drawn using a computer program called Chemsketch.

Possible uncertainties estimated before the pilot study	Results of the pilot study
The appropriateness of the intellectual level of the questions.	Students seemed to understand all of the questions and were able to give answers.
Length of the test, time problems.	The test was too long so it was separated into two tests.
Range of the answers to the questions.	Students provided a wide range of answers that produced rich qualitative data.
Unexpected outcomes of the pilot study	**Results of the pilot study**
Discrepancies between the chemical structures and printing mistakes.	All of the chemical structures were redrawn using ChemSketch and the figures were re-arranged.
Two questions were answered correctly by all of the students.	These questions were deleted from the questionnaire.

Table 4. 2: Outcomes of the Pilot Study

4.6 Content of the Tests

In this section, the content of the tests that were administered in the main study and the expected answers are given. As the respondents would not give their answers in precisely the format of words given below, the answers that are given in this section can only be taken as examples of suitable answers.

1) Recycling Process

a) Recycling of plastics is given high importance in every developed country. Statistics show that the amount of recycled plastic is constantly increasing all over Europe.

Please give three reasons why recycling plastics is important.

The Expected Answer:

- Recycling of plastics decreases the need for its raw material (crude oil) and hence helps to preserve its future. Also, recycling usually requires less energy than creating from raw materials, so it is energy-saving and the recycling of plastics prevents them from being burned and polluting the environment with toxic gases. (Nature)

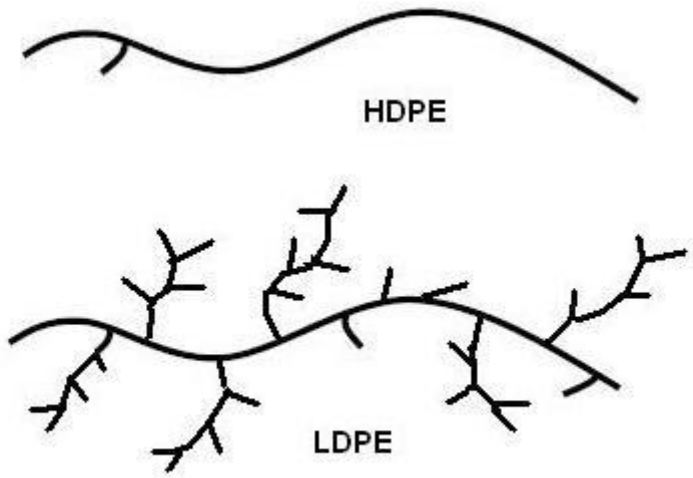
- Recycling of plastics helps to save landfill space since there are not enough places for waste any more, with an increasing population and wealth. Also, landfill has negative effects on wildlife. (Landfill)

- Recycling helps the economy as it is usually a more expensive process to create new products from raw materials rather than recycling. (Economy)

Related Learning Objective of the Macromolecules Course:

To appreciate the importance of macromolecules. One of the most common uses of Macromolecule Chemistry is the recycling process, so the importance of the recycling process is directly related to the importance of Macromolecule Chemistry.

b) HDPE (High Density Poly Ethylene) and LDPE (Low Density Poly Ethylene) are two very common types of polymer used in industry to produce a variety of products. They are both recyclable and they both have good resistance to many chemical substances. LDPE is generally used for applications that need elasticity, such as containers, dispensing bottles, wash bottles, tubing and plastic bags. HDPE is generally used for harder materials such as ballistic plates, chemical resistant piping systems and domestic furniture.



Compare the two polymers shown in terms of tensile strength and resilience using the information and molecular structures given. Explain your reasoning.

The Expected Answer:

The tensile strength and resilience features of chemical materials are mainly decided by the intermolecular forces of materials. So we should investigate those forces in these two materials. Due to the fact that these two polymers are made from the same chemical substance (poly ethylene) they should both have the same intermolecular force. Polyethylene, as can be seen from the picture, has only Van der Waals bonds (London dispersion force) causing quantum-induced instantaneous polarization or instantaneous dipole-induced dipole forces. The strength of these forces depends on the distance between molecules since as the distance increases the strength of the forces decreases. High-density polyethylene's molecules are closer to each other compared with low-density polyethylene since the less-branched polymer structure of HDPE produces its high-density property. The closer molecular structure has a stronger intermolecular force, so HDPE has more tensile strength and resilience. Moreover, branched chains of PE cannot pack closely and as a result it has low density compared with no-branched chains, and the density has a significant impact on the tensile strength of plastics.

Related Learning Objective of the Macromolecules Course:

To understand the features of polymers based on synthesis and structure. Another learning objective of the course is that an understanding of the structure of polymers is essential for classifying or deciding the features of macromolecules.

c) John's father works for a company which produces plastic bottles. John asks his father to bring him some pure HDPE and LDPE for him to experiment with. He brings them to John who takes them to his school laboratory, puts them in porcelain crucibles and combusts them.

What do you expect him to observe at the end of the combustion as a final product of the complete combustion reaction? Explain your answers.

The Expected Answer:

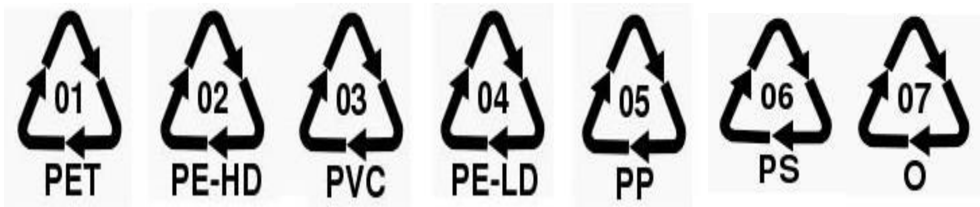
Theoretically, HDPE and LDPE are polyethylene materials and polyethylene is an organic material which is made of carbon and hydrogen. As there is no impurity (the question says 'pure') and with sufficient O_2, at the end of the combustion reaction the final products should be CO_2 and H_2O. Since CO_2 is an invisible gas and H_2O would evaporate given the reaction conditions, John would probably observe nothing at the end of combustion reaction. If the amount of O_2 is not sufficient, he would observe soot because of the C and CO products.

Related Learning Objective of the Macromolecules Course:

To develop independent learning skills such as self-assessment, creative thinking and scientific reasoning. This question aims to measure students' scientific reasoning abilities.

d) As can be seen below, plastics are identified with Plastic (Resin) Identification Codes (PIC) which should be written on the plastics.

Give three benefits of coding of plastics in this way.



The Expected Answer:

- To help the complexity of sorting and processing plastics in the recycling procedure since different types of plastic have different methods of recycling. Time and energy efficient for recycling.
- To inform the consumer about the reuse ability or recyclability of the plastics since it may not be healthy to reuse some types of plastics for unsuitable purposes. For instance, it is not convenient to use all plastics to contain food and beverages. Also, having international codes helps to sort out plastics which travel abroad.
- Recycling some plastics is not possible (some kinds of PETE) or not cost-effective (polystyrene) so it is vital to identify plastics to have a range of effective recycling processes.

Related Learning Objective of the Macromolecules Course:

To appreciate the wide use of macromolecules in our everyday life. The significance of the inclusion of macromolecules in our everyday life needs to be emphasized strongly. However, this importance is not just related to high-tech medical materials or the aerodynamic materials that are used in spacecraft, but also to the very simple materials of our everyday lives, such as food packaging or plastic bottles. This question investigates the knowledge of students on the issue and probes their misunderstandings with a broad open-ended question.

2) Fashion and Fabrics

a) Gore-Tex is the trade name of a polymer-based material which is used in fashion, especially for winter clothing. The polymer is expanded poly (tetrafluoroethene) ePTFE, (Figure 1). The key feature of the material is that although it is waterproof, it is also breathable, which means that the material does not let water get inside but it does allow steam to go out. Another commonly-used polymer is nylon (Figure 2), which has similar waterproof features but is not breathable. Different polymers have different uses depending on their characteristics. For instance, Gore-Tex material is ideal for making a jacket suitable for severe winter conditions; on the other hand, nylon would be preferred for parachute manufacture, since a breathable material would not decrease the velocity of descent as effectively.

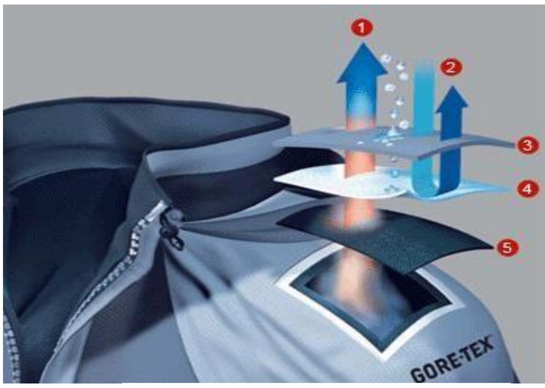


Image 1: Gore-Tex Jacket

Image 2: Parachute

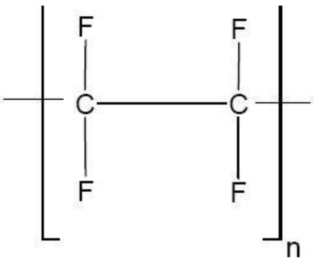


Figure 1: Poly Tetra Fluoro Ethylene

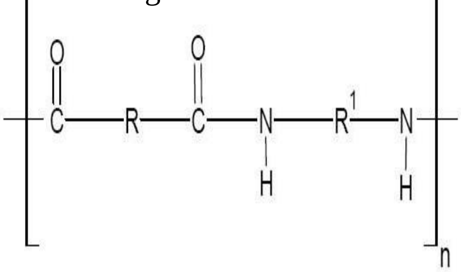


Figure 2: Nylon

Explain the waterproof and/or breathable characteristics of those fabrics using your chemistry knowledge.

The Expected Answer:

The waterproof feature of a material depends on its resistance to penetration by water. The two polymers nylon and expanded Poly (tetra fluoro ethylene) are waterproof substances as they repel water, but the waterproof feature of a textile also depends on the weaving (how tightly the yarns and fibres are woven) or the porous structure of those materials and not just the polymer that the textile is made of. So you can easily get wet even though you are wearing a nylon sock if its weaving is not tight enough. After pointing this out, we shall explain the chemistry. The specific feature of Gore-Tex stems from its tiny pores that result when the polymer (Poly (tetra fluoro ethylene)) is expanded. These pores are approximately 20,000 times smaller than a water droplet and 700 times larger than an evaporated individual H_2O molecule. So water cannot get inside the fabric but steam can get out. Because nylon has strong hydrogen bonds, however, the gaps are too small for an evaporated H_2O molecule to get through. Neither of them attracts water molecules because the hydrogen bonds in water have similar strength to the hydrogen bonds in nylon.

Related Learning Objective of the Course:

To understand how structural features control the physical features of polymers. To be able to analyse and comment on the possible physical features of polymers requires deep understanding of the structures of those macromolecules, so this question investigates the ability of students to comment on macromolecules' features using their knowledge of polymers' structures.

b) Gutta-percha and natural rubber are cis- and trans-isomers of polyisoprene and are shown below. The structure of gutta-percha contains the trans-conformation (Figure 3) and the structure of natural rubber is the cis-conformation (Figure 4) of polyisoprene. The different conformations of isomers create different physical features of the materials. Because of the general tendency of materials towards minimum energy and maximum entropy, maximally dispersed configurations have more stable structures.

Using the information given, deduce the two polymer's elasticity and brittleness at room temperature.

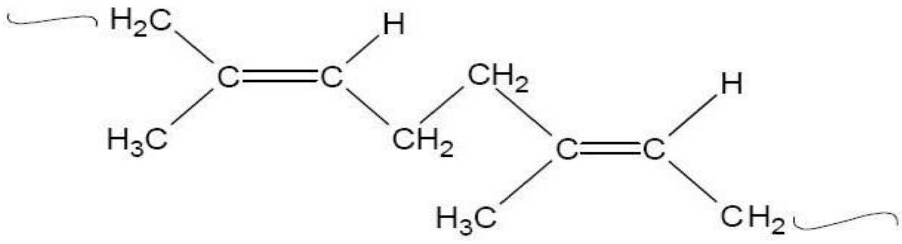


Figure 3: Trans-polyisoprene

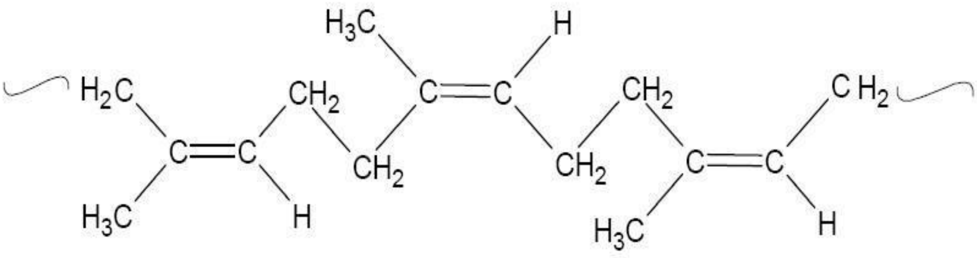


Figure 4: Cis-polyisoprene

The Expected Answer:

The trans- and cis-isomerises are forms of geometric stereoisomerism describing the location of functional groups within a molecule. Cis- and trans-isomers often have different physical features (boiling point, elasticity and so on). The difference emerges because of the positions of relatively big $–CH_2$ and $–CH_3$ groups. Trans alkenes are always more stable than cis because of the steric repulsion between the alkyl substituents in the cis compounds (except for a few cycloalkenes). So the trans-stereoisomer of polyisoprene, which is usually known as gutta-percha, is less elastic and more brittle than the cis-stereoisomer natural rubber.

Related Learning Objective of the Macromolecules Course:

To be able to draw and interpret some isomer structures of polymers. This question explored the students' understanding of the isomer structures and their impact on physical features of the polymers.

c) Kevlar is a synthetic polymer which can be synthesized through condensation polymerisation of para-phenylenediamine (1, 4-diaminobenzene) and teraphthaloyl chloride (1, 4 benzenedioyl dichloride). Kevlar (Figure 5) is used in various applications such as body armour, sports equipment and audio equipment and on a weight-for-weight basis, Kevlar is approximately five times stronger than steel.

Explain where this strength comes from.

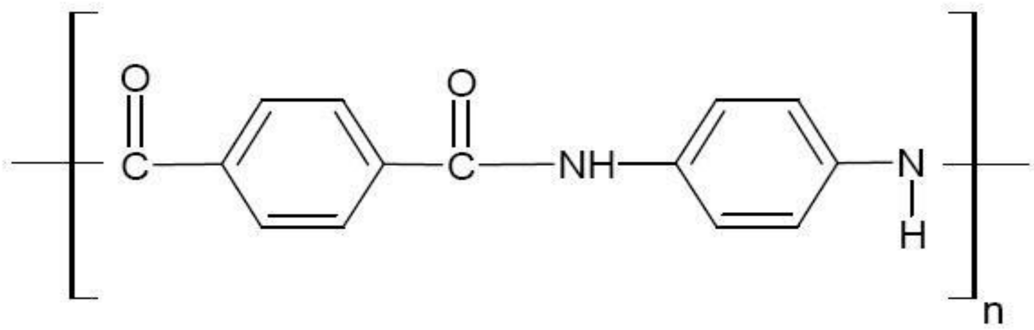


Figure 5: Kevlar

The Expected Answer:

The polymer owes its high strength to the many inter-chain bonds. These inter-molecular hydrogen bonds form between the carbonyl groups and -NH groups. High electronegative oxygen atoms and nitrogen atoms attract hydrogen atoms, and hydrogen bonds emerge. These hydrogen bonds improve the strength of the material dramatically. Additional strength stems from the non-covalent interaction between aromatic rings (aromatic stacking).

Related Learning Objective of the Macromolecules Course:

To know, and be able to comment on, some high-performance applications of macromolecules. Another learning objective of the Macromolecules course is that the course enables students to discover high-performance applications of macromolecules. This question investigates one specific use of macromolecules in military armour and sports equipment.

d) Post-use processing is seen by scientists to be just as important as the production processes of polymers themselves since polymers' self-deterioration is normally quite slow. Although Kevlar is a very strong material and widely used in industry, one of the drawbacks of the material is its recycling. Because of its very high melting temperature (around 600 C^0) it decomposes before it melts.

Because of the fact that Kevlar's life is almost infinite when it is disposed of in landfill, it is very hard to recycle: suggest another solution for the Kevlar that has already been produced in the past and is in use today.

The Expected Answer:

Kevlar could be used again, but it is typically not recycled for reasons of hardness and high cost. It is considered a material on the 'global recycling' list. Fashion designers have also grown to like the material, and environmentally friendly fashion companies take scrap pieces and integrate them into some of their newer lines. Items such as belts and headbands can be seen being made out of Kevlar. So reuse can be a solution.

Related Learning Objective of the Macromolecules Course:

To develop independent learning skills such as self-assessment, creative thinking and scientific reasoning. This question aims to measure students' creative thinking abilities.

<u>3) Bone Grafting Process</u>

PCL (poly (caprolactone), Figure 1) is a synthetic material used by scientists as a bone graft substitute *in vivo* (in the body of a living organism). The starting monomer, caprolactone, can be seen as Figure 1.

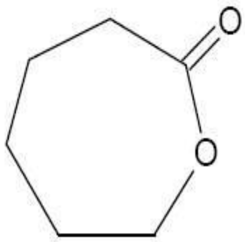


Figure 1: Caprolactone

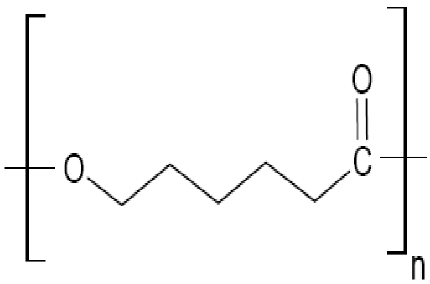


Figure 2: Repeating Unit of PCL

In a recent study, researchers tried to use PVPA (poly (vinyl phosphonic acid-co-acrylic acid)) which is made from two different monomers, vinyl phosphonic acid (Figure 3) and acrylic acid (Figure 4), with PCL as a mixture of polymers to improve bone formation. The structure of the PVPA can be seen in Figure 5.

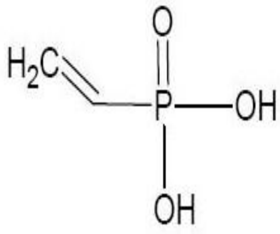


Figure 3: Vinyl Phosphonic Acid

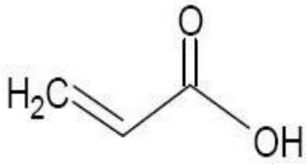


Figure 4: Acrylic Acid

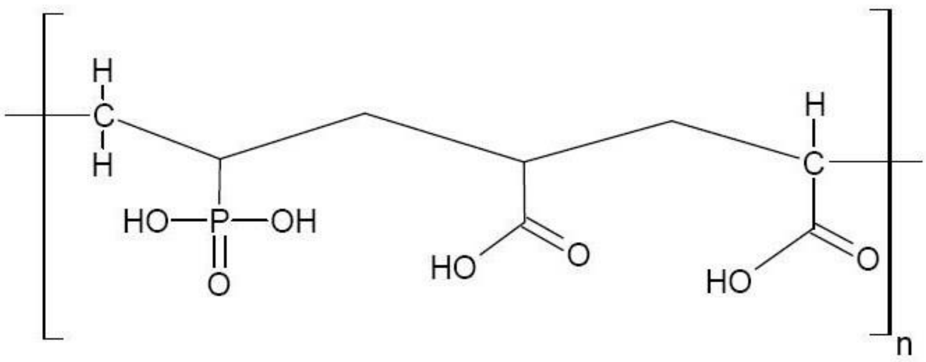


Figure 5: Repeating Unit of PVPA

a) Functional groups are atoms or small groups of atoms (usually two to four) which exhibit a characteristic reactivity when treated with particular reagents.

Name the functional groups in both polymers.

The Expected Answer:

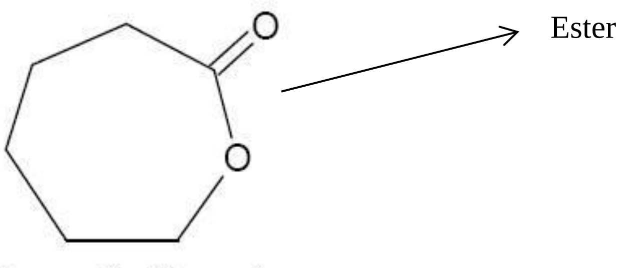


Figure 1: Caprolactone

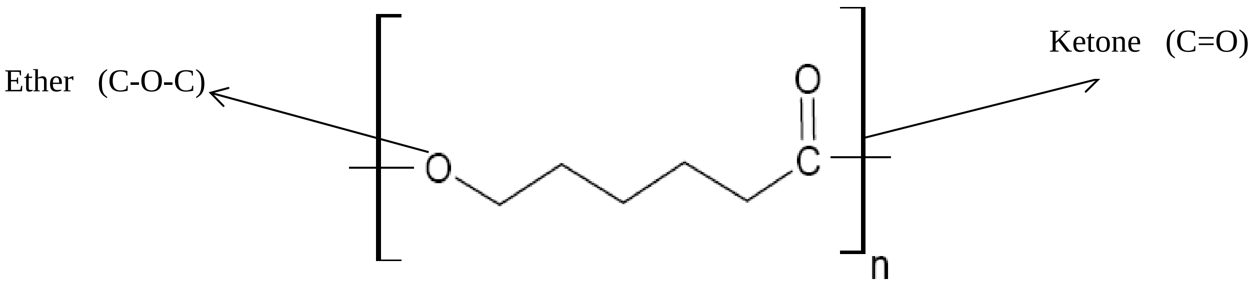


Figure 2: Repeating Unit of PCL

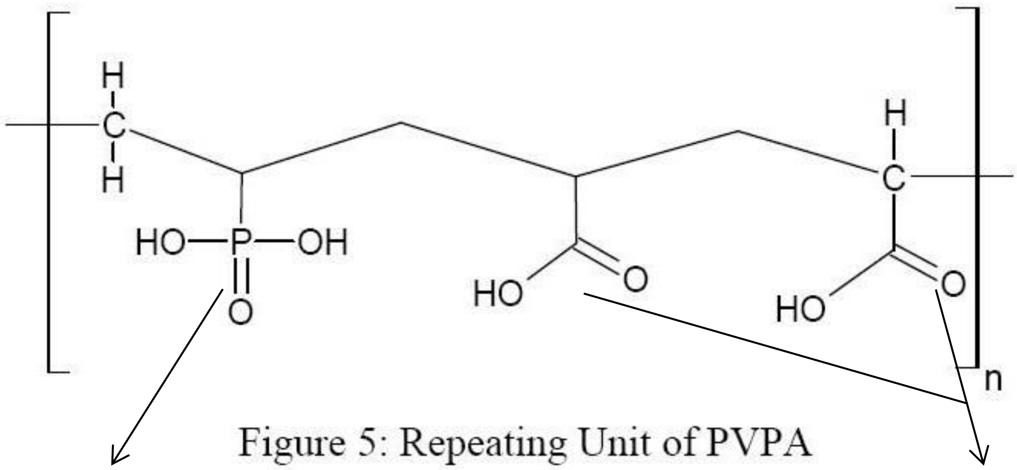


Figure 5: Repeating Unit of PVPA

Phosphoric Acid (H_2PO_3) Carboxylic Acid (OH-C=O)

Related Learning Objective of the Macromolecules Course:

To be familiarized with common functional groups of polymer used mainly in medicine. Familiarity with common functional groups is essential for understanding further reactions of polymers.

b) Two important features of chemical materials used *in vivo* (in the body of a living organism) are biodegradability and biocompatibility.

Which features of the two polymers make them biocompatible and biodegradable in the body? Please explain your answer.

The Expected Answer:

PCL and PVPA can easily be degraded by hydrolysis of PCL's ester linkages and PVPA's acid groups in physiological conditions which makes them biodegradable. As a result of those reactions, diluted carboxylic and phosphoric acid can be analysed as well as the alcohol that comes from hydrolysis of the ester linkages. Neither the polymers themselves nor the products of their hydrolysis reactions are toxic for the human body unless they are saturated, and that makes them biocompatible.

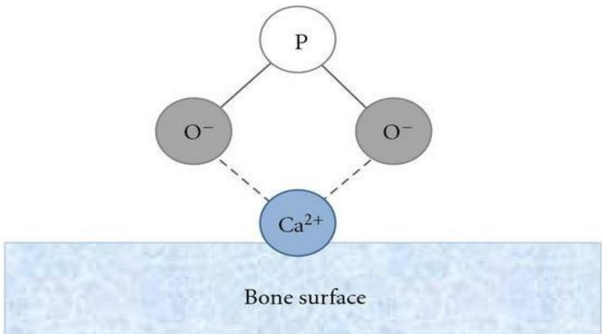
Related Learning Objective of the Macromolecules Course:

To understand biodegradability and biocompatibility features of polymers. Biodegradability and biocompatibility are two concepts which are introduced in A-level as well, and are fundamental to comprehending many of the high-performance applications of polymers, particularly in the medical applications of polymers.

c) A chelate is a chemical compound in the form of a heterocyclic ring, containing a metal ion attached by coordinate bonds to at least two non-metal ions. Chelates are vital in many human reactions especially in their role of carrying oxygen to cells in the respiration process or carrying atoms during photosynthesis. The possibility of forming chelates with the Ca^{+2} ions on the surface of bones made scientists hypothesize that adding PVPA can increase mineralisation, and therefore promote osteoblast maturation. Osteoblasts are cells found in bone; their function is to form the tissue and minerals that give bone its strength.

Draw in the space provided below the possible chelate form of the PVPA polymer.

The Expected Answer:



Related Learning Objective of the Macromolecules Course:

To understand the possible side effects of polymer applications such as chelate forms. Chelate structures have been also covered in the A-level Chemistry curriculum, so this question is designed to investigate possible side effects of polymer applications through students' understanding of chelate formation.

d) Another advantage of PVPA treatment (mixture) of PCL is that it increases the wettability of the PCL polymer. Because the hydrophilic structure increases the likelihood of a polymer's reaction with water, wettability is a highly expected feature of all biodegradable chemicals. There is experimental evidence for the advantage of adding PVPA over using PCL by itself, from the study of the water contact angles of both polymers (*see* Table 2 below).

Explain the change in wettability of PCL when it is treated with PVPA.

Table 2: Water contact angle of PCL and PCL/PVPA scaffolds

	Material	Contact angle
A)	PCL	123.3 ± 10.8°
B)	PCL/PVPA	43.3 ± 1.2°

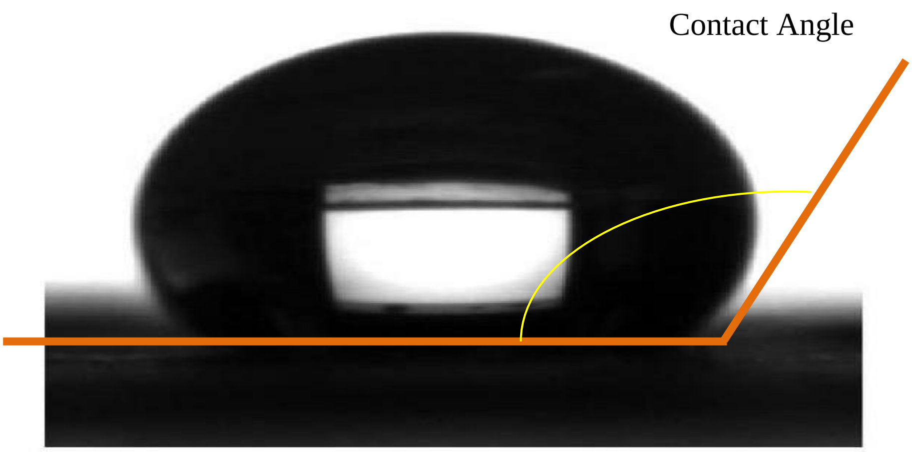


Figure A

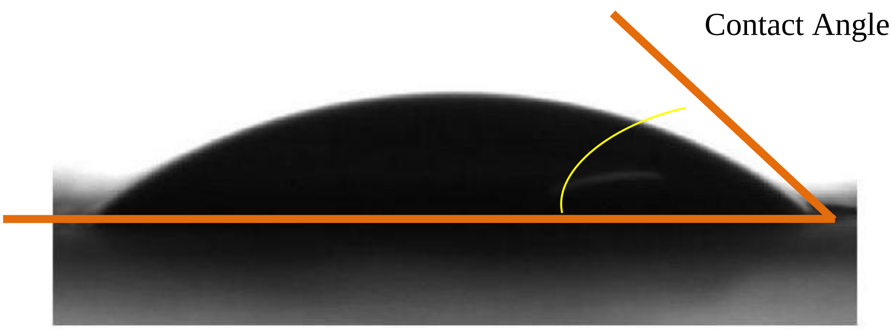


Figure B

The Expected Answer:

As can be seen from the pictures, the contact angle decreases with the addition of PVPA and this increases the contact surface of water with polymer and thus increases the wettability. PVPA has many negatively charged –COOH and –OH functional groups, and the high electronegativity of oxygen atoms exerts a greater ‘pull’ on the electrons of connected atoms and makes the group polar. Because of their polarity, these groups are attracted to water as water is also polar. PVPA/PCL has more of those polar groups and this increases its polarity and wettability. More polar groups are also the reason for more hydrogen bonds which increases the interaction with water and increases wettability.

Related Learning Objective of the Macromolecules Course:

To understand how structural features control the physical features of polymers. To be able to analyse and comment on the possible physical features of polymers requires deep understanding of the structures of those macromolecules; this question investigates the ability of students to comment on macromolecules’ features with the use of their knowledge of polymers’ structures.

e) The biomechanical strengths of the two polymers, when they are used for scaffolding around the bone structure, are:

Material	Compressive strength (MPa)
PCL scaffold	14 ± 1.2
PCL/PVPA scaffold	72 ± 4.9

It can be seen from the table that the PCL/PVPA polymer is around five times stronger than the PCL polymer. That feature of polymers increases their durability.

Explain why the addition of PVPA to the PCL increases the compressive strength almost five times using the information given and the pictures of the polymer’s structures shown.

The Expected Answer:

Mechanical strength results from the intermolecular forces of molecules. When PVPA is present, there should be more and stronger intermolecular forces between polymer chains. There should be more hydrogen bonds because of the electronegativity of carboxylic and phosphoric acids’ oxygen atoms which are much stronger than PCL’s possible Van der Waals intermolecular forces. Those intermolecular forces directly affect the physical features of the molecules such as their biomechanical strength.

Related Learning Objective of the Macromolecules Course:

To know, and be able to comment on, some high-performance applications of macromolecules. Another learning objective of the Macromolecules course is to enable students to discover high-performance applications of macromolecules. This question investigates one specific use of macromolecules in medical applications.

<u>Pipe Industry</u>

a) PVC (poly (vinyl chloride)) is a commonly-used polymer in the manufacture of pipes.

An estimate of how much energy (E) is contained in one photon of ultraviolet light of wavelength (λ) 300nm can be obtained using E = $h \times v$, where h is Planck's constant (6.62×10^{-34} Js) and v is the frequency of radiation (c/λ), c being the velocity of light which is 3×10^{8} m s^{-1}. Also, the bond dissociation energy of a carbon-chlorine bond such as is found in PVC (poly (vinyl chloride)) is 328 kJ mol^{-1}.

Using the information given, make the required calculations and discuss the consequences of it in terms of a lifetime guarantee.

Image 1: PVC pipes

The Expected Answer:

E= $h.f$ = h. $\frac{c}{\lambda}$ = 6.62×10^{-34} Js x 3×10^{8} m/s / 3×10^{-7}m = 6.62×10^{-19} j

328 kJ/mol = 328000j x $\frac{1\,mol}{6.02\,x\,10^{\wedge}23}$ = 5.45×10^{-19} j/molecule

The energy coming from the photon is 6.62×10^{-19} j and it is greater than the energy needed to break a carbon-chlorine bond in PVC (5.45×10^{-19} j/molecule), so dissociation of the bond is very possible. So selling it with a long-term guarantee would constitute a cost to the selling company.

Related Learning Objective of the Macromolecules Course:

To develop independent learning skills such as self-assessment, creative thinking and scientific reasoning. This question aims to measure students' self-assessment abilities.

b) Neoprene and isoprene are two polymers often used in the automotive industry.

Solubility depends upon the compatibility between the chemical structures of a polymer and its solvent. In the automotive industry, neoprene (Figure 1) and isoprene (Figure 2) are used in a variety of applications.

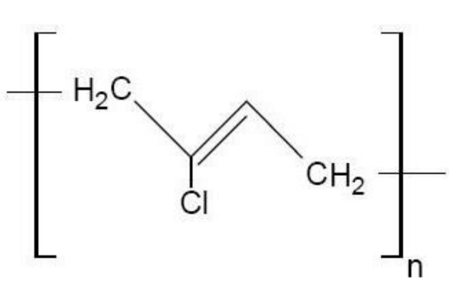


Figure 1: Neoprene

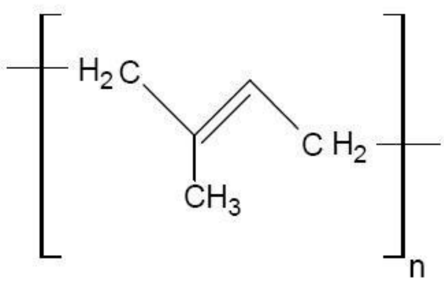


Figure 2: Isoprene

If you were an engineer designing a car, which of the two polymers shown would you use for the fuel line through which non-polar petrol flows, and which one would you use as the brake fluid pipe through which polar brake fluid flows? Give reasons for your choice.

The Expected Answer:

Since solubility depends on the compatibility of the chemical structures of a polymer and a solvent, we should check the chemical structures of neoprene and isoprene. In general, polar materials are dissolved by polar solvents and non-polar materials are dissolved by non-polar materials. This view is simplistic but quite useful. This means that a very polar solute (hydrophilic) is very soluble in highly-polar solvents. So the petrol pipe should be made of a polar polymer and the brake fluid pipe should be made of a non-polar polymer in order to prevent a dissolving reaction between the liquids and the polymers. Isoprene has carbon and hydrogen atoms whose electronegativities are very close to one another and the total dipole moment of the molecule is almost zero, so it is a non-polar material. On the other hand, neoprene has highly electronegative chlorine atoms which makes the total dipole moment of the molecule different from zero, which makes the molecule polar. So neoprene material should be used for the petrol pipe and isoprene should be used for the brake fluid pipe.

Related Learning Objective of the Macromolecules Course:

To have an introductory grasp of the structures of some inorganic polymers. In this question the impact of inorganic elements such as chlorine in the structure of polymers on features of the polymers is investigated.

c) Porosity and permeability are important parameters for polymers. However, the most significant feature of polymers which are used for the human body is their compatibility with the body. For instance, hard contact lenses are usually made from poly methyl methacrylates (Figure 3) and soft contact lenses usually employ poly hydroxyethyl methacrylate (Figure 4).

With reference to its structure, explain why poly (hydroxyethyl methacrylate) is more suitable than poly (methyl methacrylate) for soft lenses.

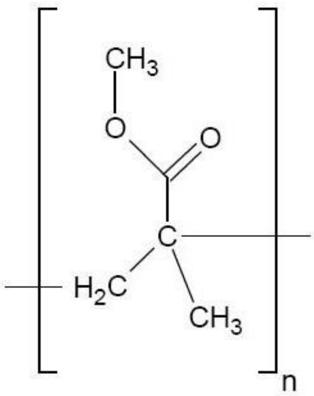


Figure 3: Poly Methyl Methacrylate

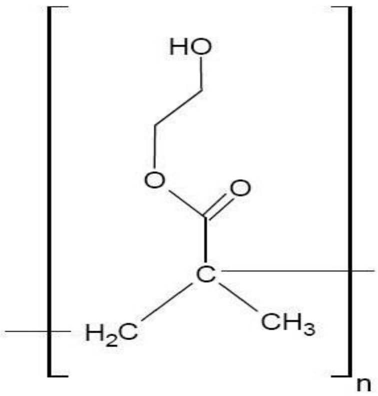


Figure 4: Poly Hyroxyethyl Methacrylate

The Expected Answer:

With reference to the polymers' structure, the difference can be identified as methyl and hydroxyethyl groups which are bonded to methacrylate molecules. First, pHEMA has a bigger side chain which would inhibit the polymer from packing tightly. Also, depending on their functional groups, one obvious difference is the hydroxyl group which increases the polarity and possibility of a reaction with water, which gives the molecule greater compatibility with water, and having an ethyl group rather than a methyl group gives pHEMA flexibility which stems from the rotation movement of the –OH group in water. In water, the polar hydroxyethyl side turns outward and the material becomes flexible, and it is this which makes the material suitable for use as contact lenses.

Related Learning Objective of the Macromolecules Course:

To appreciate the importance of macromolecules. It has been clearly stated in the learning objectives of the Macromolecules course that students are expected to recognise and appreciate the importance of macromolecules. One of the most common uses of Macromolecule Chemistry is in medical applications, so the significance of polymers has been emphasised in this question in relation to a very common use of polymers, contact lenses.

4.7 Conclusion

In this chapter, an explanation has been given of how the diagnostic questions were devised, and how the instruments used in this research study were created, piloted and administered. The aim of this chapter was to clarify the reasons behind the particular decisions made in selecting the research methodology and research methods employed. The administration of the pilot study has also been described in detail and its results have been given, and the modifications to the tests which were subsequently undertaken for their use in the main study have been explained. In the next three chapters, an examination of the answers generated by these instruments will be presented and analysed.

Chapter 5: An Overview of the Pre-Intervention Results

Introduction

This chapter is the first of three chapters that present the data collected in this research study. In this chapter, the responses of 144 first-year undergraduate chemistry students to the tests described in methodology chapter will be discussed. The outline of the chapter is that first, the development of the coding scheme will be described, then the results for each question will be presented and significant points will be discussed in detail.

5.1 Content Analysis Approach to the Qualitative Data

Students' responses to the diagnostic questions generated qualitative data which needed to be analysed in a systematic way. Three main approaches to qualitative data analysis are apparent in the literature, content analysis, thematic coding and grounded theory. In this research study, the content analysis approach was employed to analyse the collected data. Holsti (1969, p.14) described the content analysis approach for qualitative data as "a technique for making inferences by objectively and systematically identifying specified characteristics of messages". The content analysis approach has been seen as advantageous especially for its high inter- and intra-coder reliability (Holsti, 1969).

The items of the tests were diagnostic questions and generated relatively long answers. The use of one specific coding scheme helped the researcher to be consistent over time. Other advantages of the content analysis approach which have been discussed in the past are that it is a transparent and repeatable approach as well as being highly flexible (Bryman, 2008). Since the coding in the current study was undertaken by one person, it took quite a long time. For this specific research study, the investigated characteristics of the responses were their proximity to the expected answers and whether they included any sign of misunderstanding the ideas or not. The next stage after the decision to use the data analysis approach was the development of a suitable coding scheme and the coding manual.

5.2 Development of Coding Scheme and Manual

The first requirement was to create a coding scheme which could easily be applied to all of the diagnostic questions. A suitable coding scheme was vital to enable the monitoring of changes which might occur after the instruction strategy's intervention. After reading the students' responses to the questions, the need for a coding scheme which could accommodate a wide range of response types was apparent. The significance of the coding scheme for an effective and fast analysis of the data was clear. In order to create an efficient and robust coding scheme, previous research studies which had analysed qualitative data in the literature were investigated (Aikenhead *et al*,, 1987; Barker, 1994). The initial idea of the coding scheme was to think about the research questions of the study and find what is being investigated. Then the main aims of the data analysis were considered. The first aim was to see the proximity of the answers to the expected answers. Building on this idea, it was decided to create a coding scheme that could effectively separate correct, incorrect and partly correct answers from one another. The second main aim was to detect, if there were any, misunderstandings of the students about the ideas discussed. So the coding scheme was created on the basis of these two main criteria.

5.2.1 The First Coding Scheme

After the decision to use the content analysis approach to analyse the data was made, attempts to devise a coding scheme started. To prepare an appropriate coding scheme, codings were first applied to the question about the recycling process of polymers. The reason for choosing that question was the very high response rate which it generated. From the first impression, this question was the most answered question in the test so it was estimated that a coding scheme that would fit that broad range of answers might fit the other questions equally well. Second, as the test applied the funnel approach, the first question was considered to be the easiest to answer. So the analysis of the responses to this question was expected to be easier than for other questions. Moreover, this question was a bullet points type of question which generated clearer explanations rather than more complex explanations.

Table 5.1 shows the first attempt at coding for the *Recycling Process* question. Each answer was given a code comprising one letter and one number. The letter corresponds to the final judgement of the answer being correct, partially correct or incorrect, and the number corresponds to the more detailed specification of that judgement and relates to possible signs of the misunderstanding of ideas. For example, A1 represented correct with no evidence of misunderstanding.

CODE	EXPLANATION	NUMBER of ANSWERS	PERCENTAGE
A1	All correct with no evidence of misunderstanding		
A2	Correct with some evidence of misunderstanding		
B1	Partially correct, incomplete answer with no evidence of misunderstanding		
B2	Partially correct, incomplete answer with some evidence of misunderstanding		
C1	Wrong answer, evidence of misunderstanding		
C2	Wrong answer with irrelevant response		
D1	Uncodeable		
D2	No Response		
D3	Don’t Know		
D4	Other Comments		

Table 5.1: The First Coding Scheme

Although at first this scheme seemed sufficient to categorise the responses in a systematic way, as soon as the analysis of the data started, some issues became apparent in terms of clarity.

First, the categorisation by letter seemed appropriate. The proximity of the answers to the expected answers was easily symbolised with letters, using A for a complete answer, B for an incomplete answer, C for a wrong answer and D for no answer. However, the categorisation by number did not seem right. The number 1 was used to categorise A and B responses as showing no sign of misunderstanding, but the code C1 represented a wrong answer with a sign of misunderstanding the ideas. With the same absence of logic, 2 used with A and B represented some signs of misunderstanding but used with C it still represented no sign of misunderstanding, which was clearly illogical. So it was decided to replace the C1 code with C2. This made the categorisation clearer as the letters now represented the completeness of the answers (complete, incomplete, wrong and no answer), and the numbers signified a sign of misunderstanding when used with A, B and C (with 1 for no sign of misunderstanding and 2 for some signs of misunderstanding).

Another issue was related to the questions which were not answered. As can be seen from Table 5.1, non-answered questions were coded with the letter D, and D1 represented that the response was ‘uncodeable’, but full analysis of the responses to the first question showed that with the use of all the other codes in the scheme, there were no uncodeable responses. So the table was revised and in the new table, the code D1 was used to represent ‘no response’.

CODE	EXPLANATION	NUMBER of ANSWERS	PERCENTAGE
A1	All correct with no evidence of misunderstanding		
A2	Correct with some evidence of misunderstanding		
B1	Partially correct, incomplete answer with no evidence of misunderstanding		
B2	Partially correct, incomplete answer with some evidence of misunderstanding		
C1	Wrong answer with irrelevant response		
C2	Wrong answer, with some evidence of misunderstanding		
D1	No Response		
D2	Don't Know		
D3	Other Comments		

Table 5.2: The Final Coding Scheme

In the final version of the coding form, shown as Table 5.2, the coding scheme seemed to cover all the responses of students. Analysis of the other questions therefore started using the coding scheme presented in Table 5.2.

5.3 Results of the Pre-intervention Data Analysis

Before the presentation of the results for each question, some details about the pre-intervention data analysis in general will be given. First, it is useful to point out that there was no item which was not coded. The coding scheme prepared as described above covered all the answers given to the questions. Tables 5.3 and 5.4 show the numbers of the valid answers to the tests. In these tables, valid values show the number of students who took part in both pre- and post-tests; whereas missing values show the number of students who did not take part in either pre- or post-test.

		Pre-Recycling Question	**Pre-Branching Question**	**Pre-Combustion Question**	**Pre-PIC Question**	**Pre-Fashion Question**	**Pre-Isomerism Question**	**Pre-Kevlar's Strength Question**	**Pre- Reuse of Kevlar Question**
	Valid	82	82	82	82	82	82	82	82
	Missing	0	0	0	0	0	0	0	0

Table 5.3: Valid Answers for Test 1

		Pre-Func. Groups Question	**Pre-Biodeg. and Biocomp. Question**	**Pre-Chelate Question**	**Pre-Wettability of Materials Question**	**Pre-Mech. Strength of PVPA/PCL Question**	**Pre-Calculation Question**	**Pre-Polarity Question**	**Pre-Contact Lenses Question**
	Valid	62	62	62	62	62	62	62	62
	Missing	0	0	0	0	0	0	0	0

Table 5.4: Valid Answers for Test 2

As can be seen from Tables 5.3 and 5.4, in total 144 students participated in the research study, and there were no missing test responses. Another point is that the green-coloured test, Test 1, was preferred by more students. Previous research studies on the impact of the stationery colour on response rate have shown that green envelopes were predominantly opened first, followed by blue. Red envelopes were consistently opened last (Bender, 1957). However, more recent studies show no statistically significant impact of the stationery colour on response rate (Greer & Lohtia, 1994; McCoy & Hargie, 2007). These studies imply that students' preference for green-coloured papers was a coincidence.

The results of students' coded responses to the diagnostic questions in the pre-test are presented in tables. Each table presents four different types of data in four columns. The first, labelled 'Frequency,' simply reports the total number of responses that coded with a specific code from the coding scheme (*see* Table 5.2). The second column, labelled 'Percent,' provides a percentage of the total responses that coded with each code. The third column, labelled 'Valid Percent,' is a variation of the 'Percent' column; it recalculates the percent without including the missing responses. If the 'Valid Percent' equals 'Percent', that means there was no missing response. The fourth column, labelled 'Cumulative Percent', adds the percentages of each region from the top of the table to the bottom, culminating in 100%. This last column is useful to get a sense of what percentage of responses is coded below a specific code. For instance, it is very useful to see what percentage of responses coded with B and C which refers to incomplete and wrong responses of students.

5.4 Test 1

1) Recycling Process Question

The recycling process question investigated students' knowledge acquisition about the recycling process and their misunderstandings about recycling. The preamble gave the information that the amount of plastics recycled has increased recently and asked students to give three reasons for the importance of recycling.

Pre-Recycling Question

Code		Frequency	Percent	Valid Percent	Cumulative Percent
C2	Wrong answer with some evidence of misunderstanding	2	2.4	2.4	2.4
C1	Wrong answer with no evidence of misunderstanding	2	2.4	2.4	4.9
B2	Incomplete answer with some evidence of misunderstanding	18	22.0	22.0	26.8
B1	Incomplete answer with no evidence of misunderstanding	32	39.0	39.0	65.9
A2	Correct with some evidence of misunderstanding	1	1.2	1.2	67.1
A1	All correct with no evidence of misunderstanding	27	32.9	32.9	100.0
	Total	82	100.0	100.0	

Table 5.5: Pre-Intervention Responses to the Recycling Process Question

The frequencies of the responses given to this question are shown in Table 5.5. The first feature that appears very clearly in Table 5.5 is that all of the students gave an answer to the question, so there was no answer coded D. This question had one of the highest numbers of expected answers. The reason for the high figure may be the context of the question. The recycling process is a very popular topic in Polymer Chemistry and is covered well by the majority of students. Moreover, it was expected that there might be a problem maintaining students' interest in the test, especially for the pre-intervention phase of the research study. Because the students had not taken the course at that stage, challenging questions, particularly in the first part of the test, could have had a hampering impact on the students' willingness to participate in the study at the post-intervention data collection phase. So the first question was intentionally on a relatively less-challenging topic and at a less-challenging level. So a high percentage of A-coded answers was anticipated. It can be seen from the cumulative percentage column that 65.9% of the responses were coded with either B or C which refer to incomplete and wrong answers, respectively.

The answers which were given code A1 amounted to 32.9%; these students provided the full expected answer to the question. Despite the high number of correct answers for the question, the total number of students who gave an answer with some sign of misunderstanding was also quite high. The percentage of responses coded 2 was 25.6%. This shows that more than a quarter of the answers had some sign of misunderstanding.

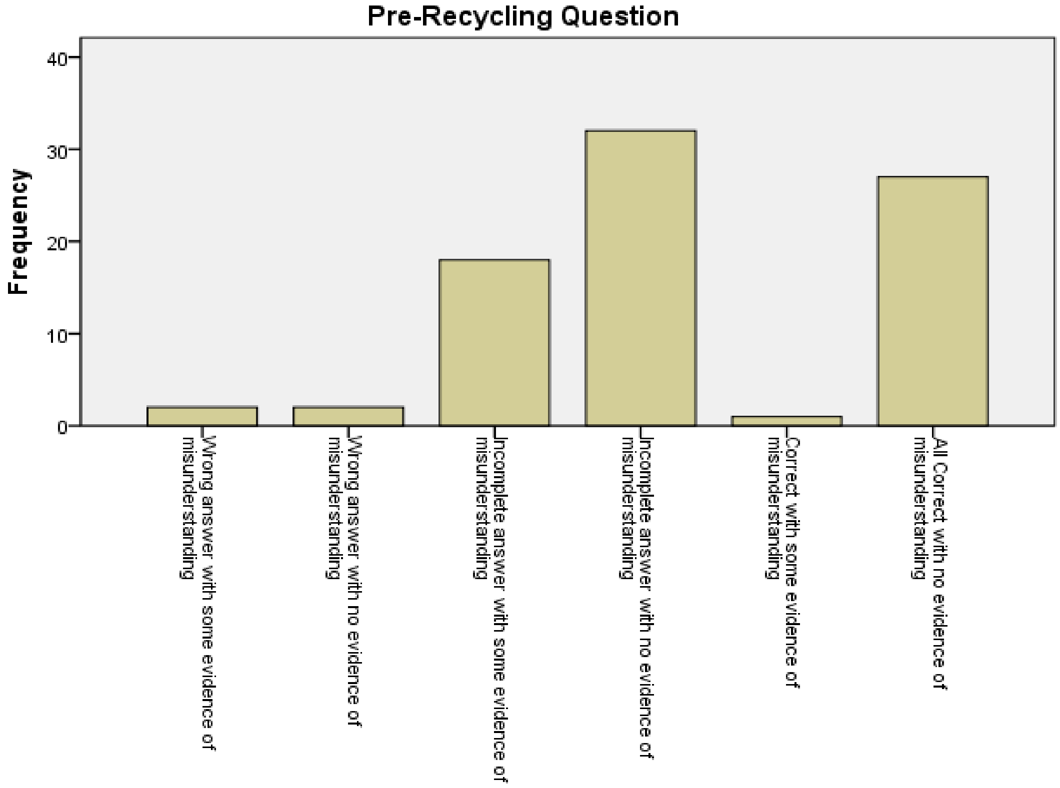


Figure 5.1: The Frequencies of the Responses to the Recycling Process Question

Students' misunderstandings generated several themes. The most common misunderstandings were about the structure of plastics. Quite a few students thought that all plastics are made entirely from oil or that all plastics can be recycled.

Examples of answers with some sign of misunderstanding include:

All of the plastics are made of oil so we have to decrease reliance on oil sources …

We can recycle all of the plastics as it is cheaper than producing new ones …

To be able to re-use them …

Many plastics are made of crude oil, but plastics can be made of many other elements and compounds such as natural gas. Moreover, plastics can include a variety of polymers which encompass different atoms in their structure. For instance, polyvinyl chloride (PVC) contains chlorine, nylon contains nitrogen, Teflon contains fluorine and crude oil does not include any of those elements. If all plastics were made only from crude oil, they would not include these atoms.

The second most common misunderstanding in the responses was that some students believed that every plastic can be recycled, but not every plastic is recyclable or preferred for recycling. In addition to these misunderstandings, there were also some students who were confused about the terms ‘recycling’ and ‘re-use’. Even though the question asked students to give three reasons for the importance of recycling, some answered the question as if re-use and recycling are two words describing the same phenomenon and can be used interchangeably. However, reuse is a different idea from recycling. It was surprising to see such a variety of misunderstandings about a topic which is widely covered in A-level chemistry and also emphasized in citizenship education.

One possible reason for these misunderstandings could be the everyday use of the word ‘recycling’. It has been shown in the literature that every student has a rich accumulation of interrelated ideas that constitute a personal system of common-sense beliefs about ideas used in everyday life, and that these ideas can differ quite widely from the scientific use of the terms (Champagne, Klopfer & Anderson, 1980). So taking this into consideration, the high percentage of 2-coded responses, suggesting signs of misunderstanding the ideas, for this question is not very surprising since recycling is a word deeply embedded in students’ everyday life.

2) Branching Question

This question probed students’ fundamental knowledge of branching in polymers and the impact of branching on polymers’ physical properties. In the question, the structures of two polymers were given and their tensile strength and resilience features had to be interpreted by the students by looking at the structures of the two polymers. The responses are given in Table 5.6 and show that 62.2% of the students were able to give the expected answer with no sign of misunderstanding.

For instance;

HDPE has a regular structure, less branching than LDPE so the monomers can pack closely together that maximise intermolecular bonding in the HDPE which is why it is stronger/denser. That increases the tensile strength and resilience. In LDPE the chain branching means bonding is not as strong.

Pre-Branching Question

Code		Frequency	Percent	Valid Percent	Cumulative Percent
D	Don't know, No Response, Other Comments	8	9.8	9.8	9.8
C2	Wrong answer with some evidence of misunderstanding	6	7.3	7.3	17.1
C1	Wrong answer with no evidence of misunderstanding	5	6.1	6.1	23.2
B2	Incomplete answer with some evidence of misunderstanding	1	1.2	1.2	24.4
B1	Incomplete answer with no evidence of misunderstanding	7	8.5	8.5	32.9
A2	Correct with some evidence of misunderstanding	4	4.9	4.9	37.8
A1	All Correct with no evidence of misunderstanding	51	62.2	62.2	100.0
	Total	82	100.0	100.0	

Table 5. 6: Pre-Intervention Responses to the Branching Question

The high percentage of expected answers suggests that the students were able to make sensible connections about the branched structures of the polymers and the impact of branching on the properties of the polymers. The number of the students who gave an answer with a sign of misunderstanding the idea of branching was low. The most common misunderstanding was that some students thought that more side chains meant more intermolecular bonding. For instance,

LDPE is more flexible, it has branches which can bond and connect in different ways more that HDPE, so it is more elastic.

Those students thought that molecules with more side chains can have stronger molecular forces. This finding can be related to a general intuitive rule (Stavy & Tirosh, 1996) that ‘the more of A (the salient quantity), the more of B (the quality in question)’. However, because molecules with side chains have the steric effect of these side chains, they cannot get close to each other and so cannot form strong intermolecular bonds. These students seemed not to be able to comprehend the three dimensional positions of polymers but imagined chemical structures as two-dimensional drawings. In two-dimensional pictures, polymers’ side chains may seem ‘pronged’ and more likely to form bonds, but the steric effect should be considered to have better understanding of the bond formation of those structures.

As can be clearly seen from the frequency bar chart at Figure 5.2, the question generated a variety of responses, and the variety of the codes allocated suggest the inconsistency of the students’ ideas of branching in polymers.

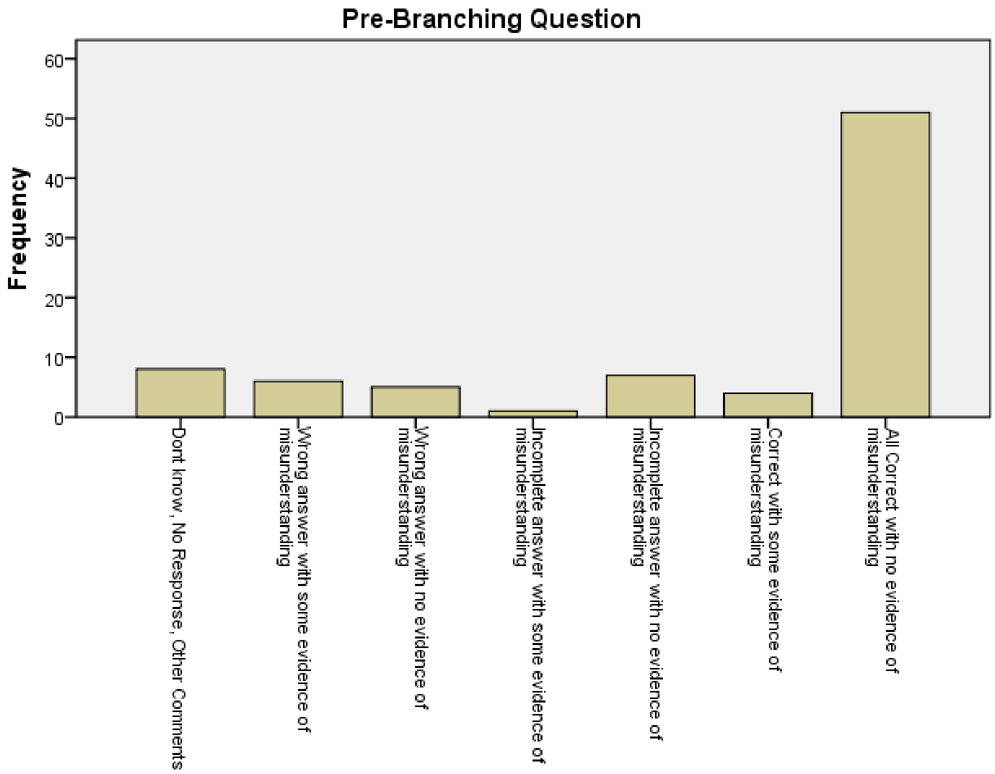


Figure 5.2: The Frequencies of the Responses to the Branching Question

3) Combustion Question

This question was intended to investigate the impact of the applied instruction strategy on students' scientific reasoning. As has been discussed in the literature, students have some ideas about everyday life phenomena before they come to the learning environment (Champagne *et al*., 1980; Gilbert & Osborne, 1980), so it is sensible to assume that every student has his/her own ideas about combustion and more particularly about the combustion of plastics. These common-sense intuitive ideas are the product of years of experience of occasions of combustion and are possibly quite useful in students' daily experiences. However, these ideas may differ widely from what chemistry courses teach to students. Because this question included materials which are very common in everyday life, it can be hard to approach the problem with a scientific attitude. For instance, HDPE and LDPE are quite common raw materials of the plastic bottles and the plastic bags that we use in our everyday life. If students consider the combustion of plastic bottles or plastic bags – which they have possibly seen burning before – they would develop one way of explaining the phenomenon in their way of thinking. In this way of thinking, their conclusion would be that the end product is a sticky, black, filthy mass. Nevertheless, in a purified laboratory environment, chemistry teaches to students the following chemical reaction which has no observable end products at the end of combustion reaction:

$$(CH_2\text{-}CH_2)n + (n+2)\ O_2 \longrightarrow 2\ CO_2 + 2n\ H_2O$$

As can be seen from the reaction, if enough O_2 is available, the end products are CO_2 (a gas) and H_2O (water), neither of which will be observed with the naked eye at the temperature of the reaction. Those two different scenarios, one drawn from everyday life experiences and the other taught in science classes, can sometimes be mutually exclusive.

The question sought to monitor any shift in students' thinking about these two different explanations of the combustion reactions. Any possible shift will be used as an argument to judge students' scientific reasoning abilities. The frequencies of the coded responses are given in Table 5.7.

Pre-Combustion Question

Code		Frequency	Percent	Valid Percent	Cumulative Percent
D	Don't know, No Response, Other Comments	29	35.4	35.4	35.4
C2	Wrong answer with some evidence of misunderstanding	7	8.5	8.5	43.9
C1	Wrong answer with no evidence of misunderstanding	20	24.4	24.4	68.3
B2	Incomplete answer with some evidence of misunderstanding	1	1.2	1.2	69.5
B1	Incomplete answer with no evidence of misunderstanding	4	4.9	4.9	74.4
A1	All Correct with no evidence of misunderstanding	21	25.6	25.6	100.0
	Total	82	100.0	100.0	

Table 5.7: Pre-Intervention Responses to the Combustion of HDPE and LDPE Question

Table 5.7 shows that 25.6% of the students gave an answer coded A1. These students gave the expected answer to the question. For this question, it is argued that the students who gave the correct answer had better scientific reasoning abilities. Scientific reasoning requires some data generated through the sorts of interactions with the real world assumed in the predictions derived from the model which requires an ability to transfer from real world to model's world appropriately. In this question, the data generated through the sorts of interactions with the real world is the students' observations of the combustion of HDPE and LDPE polymers. Predictions derived from the model are the end products of combustion reactions of these polymers which are CO_2 and H_2O. It is argued here that the students who gave the correct answer to this question had better ability to transfer from real world to model's world and *vice versa*; hence they had better scientific reasoning.

At 32.9%, however, wrong answers to this question formed the highest percentage. The majority of the wrong answers were similar to these examples:

A melted, twisted, burned, filthy, mass. And a crucible which is a nightmare to clean

A black carbon.

These incorrect answers suggest that some students struggled to use their chemistry knowledge and/or their scientific reasoning attributes when they were confronted with problem situations. As chemists, the expected response would be to write the chemical structures, the related chemical reaction, and the possible end products.

The number of responses with a sign of misunderstanding was relatively high. This result may stem from the argument which suggests that students who have common-sense explanations about everyday life phenomena which are taught in formal science have to go through a major reconceptualization process. The challenging structure of this reconceptualization process may be an explanation for high percentage of responses coded 2.

One of the very significant findings of this question is that some students were still struggling with some misunderstandings that have been established in the literature as school pupils' misunderstandings in science, even though the students who participated in this study had reached the tertiary level of education. Some of the students gave answers such as,

... Because we burn them their mass should lessen ...

The LDPE will give out more energy as it has weaker intermolecular bonding...

The misunderstanding that burning always causes substances' weight to reduce is a common misunderstanding in the literature, particularly in research studies of young age groups (Driver, 1985). However, to come across the same misunderstanding among first-year university students may be an argument to support the robustness of such misunderstandings.

It is well-known in chemistry that in iron's combustion reaction, the observed product, rusted iron, has more mass than iron due to the added oxygen's mass. An example of that type of combustion reaction is:

$$4\,Fe + 3\,O_2 \longrightarrow 2\,Fe_2O_3$$

As can be seen from the reaction in the combustion of iron, the reactants are iron and oxygen, the end product is iron (III) oxide. The mass of iron filings increases after combustion since the mass of oxygen will be added to the mass of iron.

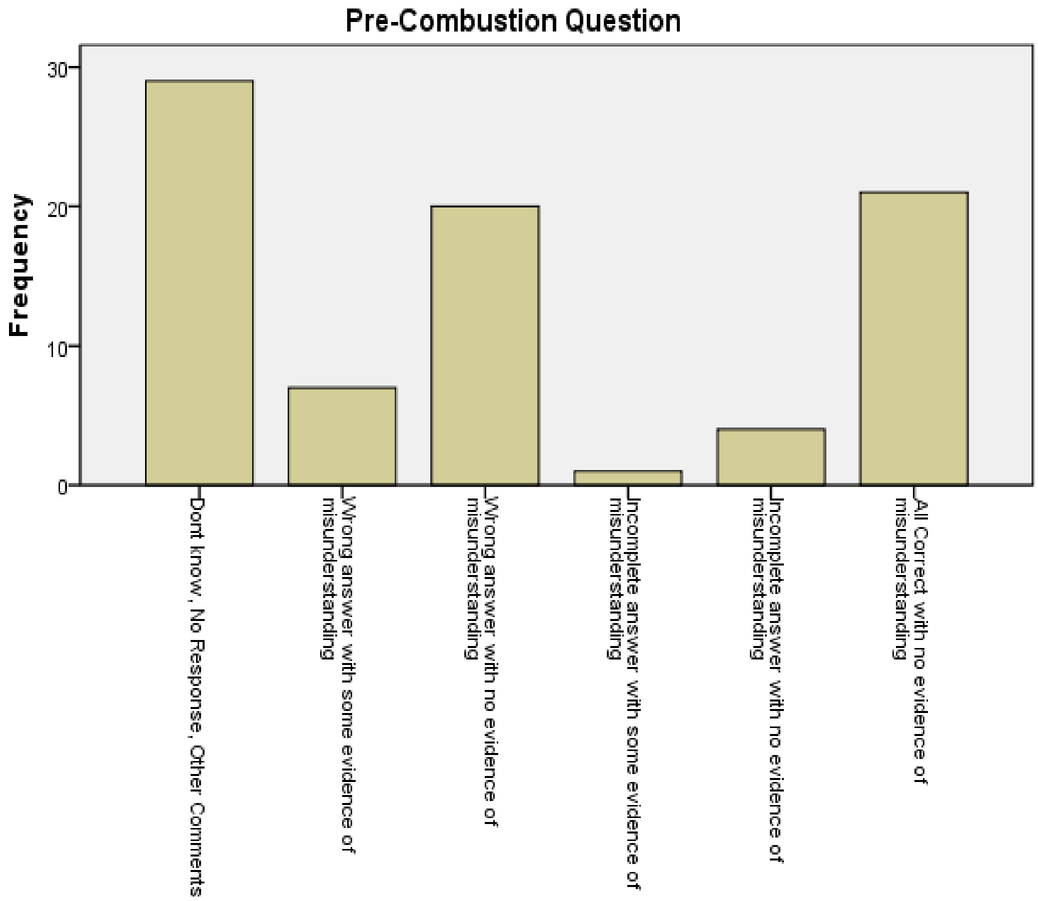


Figure 5.3: The Frequencies of the Responses to the Combustion Question

Again, the frequency bar chart in Figure 5.3 visualises the differences in the frequencies of the students' coded responses and the high frequency of D-coded answers becomes apparent.

4) Plastic Identification Codes Question

In the PIC question, students were asked about their ideas on PICs. This question was intended to measure students' knowledge acquisition about the everyday life applications of polymers.

Pre-PIC Question

Code		Frequency	Percent	Valid Percent	Cumulative Percent
D	Don't know, No Response, Other Comments	7	8.5	8.5	8.5
C1	Wrong answer with no evidence of misunderstanding	5	6.1	6.1	14.6
B1	Incomplete answer with no evidence of misunderstanding	60	73.2	73.2	87.8
A1	All Correct with no evidence of misunderstanding	10	12.2	12.2	100.0
	Total	82	100.0	100.0	

Table 5.8: Pre-Intervention Responses to the PIC Question

The coded responses are presented in Table 5.8. As can be seen from the table, the most common code for this question, at 73.2%, was B. Code B signifies an incomplete, partially correct answer. The majority of the students were able to give partially correct answers to this question, but they could not provide a fully correct answer. This suggests that the students had clear gaps in their knowledge about the types, processing and recycling of polymers.

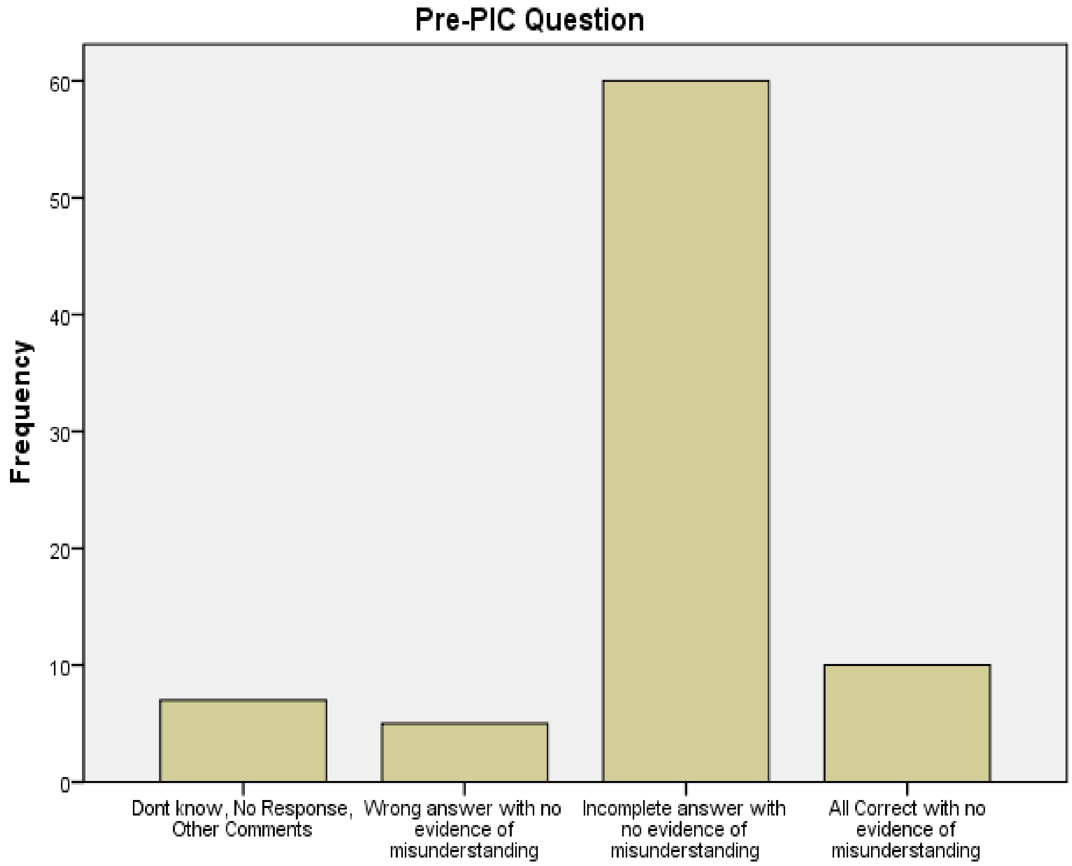


Figure 5.4: The Frequencies of the Responses to the PIC Question

As can be seen from Figure 5.4, this question did not generate any responses which included a sign of misunderstanding. Students' pre-intervention knowledge on the issue was less problematic in quality but it was not fully satisfactory. Their answers seemed to focus more on the context of the question than the content.

An example of students' answers coded A1 is

… to be able to identify plastics to see their suitability of use, to see if the plastic is recyclable and to help to the separation of plastics for their recycling process.

One interpretation that could be drawn is that the students' answers were not satisfactory in terms of quantity. The majority of the students failed to give answers which offered three valid reasons for the use of PIC. They managed to find one or two reasons so their answers were coded B. The major expected improvement for the responses to this question is the number of complete answers given.

5) Fashion and Fabrics Question

The intention of this question was to observe students' ability to transfer their knowledge of chemistry to novel contexts related to polymer chemistry. As discussed in the literature review, the ability of knowledge transfer is a valued aim of modern science education, and instruction strategies which contribute to students' ability to transfer their knowledge to different contexts are considered to be meritorious.

In this question, the students were asked to explain the waterproof and/or breathable features of fabrics using their knowledge of chemistry. The intention was to investigate students' success at working out the possible features of the polymers by using their chemistry knowledge.

This question was relatively more challenging than others in nature as it included relatively more complicated polymer structures compared with the other questions in the test. The highly challenging structure of the question is directly reflected in the responses and this question generated one of the lowest percentages of codes A and B. Table 5.9 shows the frequencies of responses.

It is clear from Table 5.9 that a very high proportion of the undergraduate chemistry students, almost half of them at 48.8%, gave D-coded responses to this question by either leaving it blank or declaring that they did not know the answer. A reason for this high figure could be that the students' ability to transfer knowledge was quite low before the intervention of the instruction strategy. Another reason might be that they were put off by the complex structures and names of the modern polymers used in fabrics. One of the fabrics that was given as an example in the question was Gore-Tex. Gore-Tex is the trade name of the polymer (expanded PolyTetraFluoroEthene) based material which is used in textiles, especially for winter clothing. Even though PTFE is covered in A-level chemistry and Gore-Tex was explained to be PTFE in the question's preamble, still the novelty of the name might have been challenging for the students.

Pre-Fashion Question

Code		Frequency	Percent	Valid Percent	Cumulative Percent
D	Don't know, No Response, Other Comments	40	48.8	48.8	48.8
C2	Wrong answer with some evidence of misunderstanding	2	2.4	2.4	51.2
C1	Wrong answer with no evidence of misunderstanding	17	20.7	20.7	72.0
B2	Incomplete answer with some evidence of misunderstanding	2	2.4	2.4	74.4
B1	Incomplete answer with no evidence of misunderstanding	13	15.9	15.9	90.2
A1	All Correct with no evidence of misunderstanding	8	9.8	9.8	100.0
	Total	82	100.0	100.0	

Table 5.9: Pre-Intervention Responses to the Fashion and Fabrics Question

Nevertheless, confronting students with a challenging question seemed to make them express their ideas more broadly. This situation created an opportunity to investigate students' misunderstandings in a broader sense. For instance,

The poly tetra fluoro ethylene is waterproof due to the F attached the carbon chain. It is a very small, highly electronegative molecule that stops the water by repelling it but leaves enough space for other non-polar molecules to pass through the material.

First, this student seems to attribute the waterproof feature only to the polymer, however, the waterproof feature of fabrics is also related with the way that fabrics are woven. If you wear a fabric which is made of highly water-repellent polymer but is woven very loosely, you would still get wet. Second, and maybe more interestingly, this student seems to think that steam has a different chemical structure from water. First, he stated that highly electronegative fluorine repels water as water has a polar structure. Then he explained that the matter passing through, which refers to steam, is non-polar. However, the phase change from liquid to gas is a physical change which does not influence the chemical structure of materials.

With only 9.8% of expected answers, this question was one of the least successfully answered questions. Another possible reason for that low percentage might be the fact that the question required students to combine a broad range of knowledge from their chemistry background and then use it in a novel context. It requires analysis, synthesis and evaluation of knowledge, which is a multiple process seen as the most challenging in the cognitive domain (Bloom *et al*., 1956).

The frequency bar chart shown as Figure 5.5 clearly shows that the frequency of wrong answers was quite high for this question as well as the responses with no answer at all. Although the question seems to be disadvantageous considering the high percentage of D-coded responses, one possible advantage of the question is that it leaves quite a big space for improvement in the post-intervention data analysis.

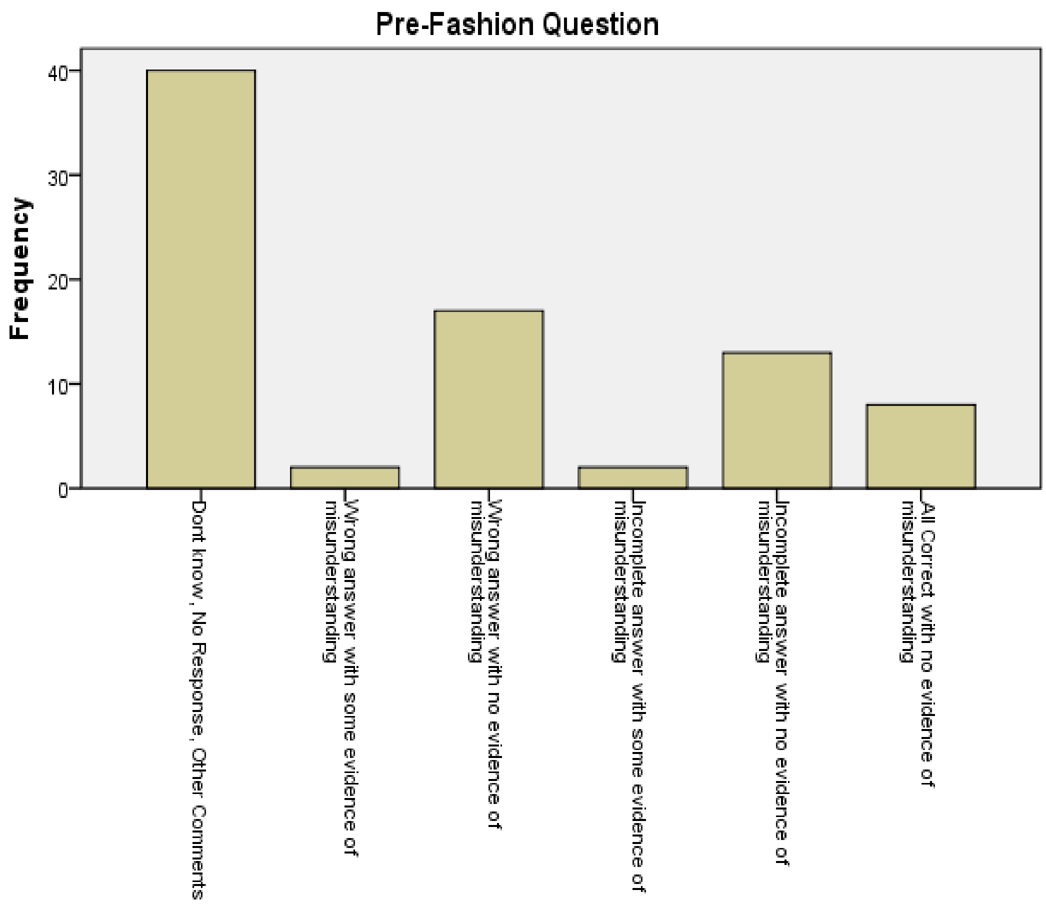


Figure 5.5: The Frequencies of the Responses to the Fashion and Fabrics Question

6) Isomerisation Question

This question was intended to measure students' understanding of the structures of cis- and trans- stereoisomers in polymers and the impact of these different stereoisomerisms on polymers' behaviours in chemical reactions. Stereoisomerism is a highly important topic for polymer chemistry as well as organic chemistry and it is also covered in many A-level syllabuses. Even though isomerisation has been covered briefly at A-level and more in depth in some other first-year courses that the students had already undertaken (such as Organic Chemistry), the results show that many students struggled to give the expected answer to this question. Table 5.10 presents the responses of the students in numbers and percentages.

Table 5.10 shows that 13.4 % of the students were able to give the correct answer to this question. Moreover, there were only 8.5% of the responses which were coded as showing signs of misunderstanding. Some students thought that cis- and trans- isomers could have different numbers of monomers or different numbers of double bonds. However, cis- and trans- isomers are geometrical isomers and are used to describe the relative orientation of functional groups within a molecule. Since they are geometrical isomers of the same molecule, the number of the double bonds or the number of monomers is exactly the same for both cis- and trans- isomers.

Since trans- isomers have more double bonds than cis- isomers, they should be stronger and more stable. Since trans- polypropylene is more brittle.

On the other hand, there were quite a few expected answers including this example:

The trans- conformation has substituent groups as far away as possible from one another. This decreases strain and as such, is a lower energy conformation. This should make it a more stable structure and I would expect it to be less elastic, more brittle than cis- conformation.

Pre-Isomerism Question

Code		Frequency	Percent	Valid Percent	Cumulative Percent
D	Don't know, No Response, Other Comments	30	36.6	36.6	36.6
C2	Wrong answer with some evidence of misunderstanding	7	8.5	8.5	45.1
C1	Wrong answer with no evidence of misunderstanding	14	17.1	17.1	62.2
B1	Incomplete answer with no evidence of misunderstanding	20	24.4	24.4	86.6
A1	All Correct with no evidence of misunderstanding	11	13.4	13.4	100.0
	Total	82	100.0	100.0	

Table 5.10: Pre-Intervention Responses to the Isomerisation Question

Another misunderstanding revealed in this question was that the students attempted to explain the chemical features of those polymers by considering the macro-level features of those polymers. However, the correct answer required consideration of the micro-level features of the polymers. Some examples of the responses with some sign of misunderstanding are

Cis- will appear to be more straight-chained than trans-, so stronger and less elastic. Trans- should be able to bend more easily and hence more elastic.

Cis- as its monomers seems to be closer to each other, should be stronger and more brittle than trans-.

In the first example, the student talks about the cis- conformation of the polymer and claims that it would be stronger as it will be more straight-chained. The misunderstanding is that the student evaluated the strength of the polymer in the same way that people would evaluate materials at macro-level. For example, when guessing the strength of a piece of wood, if it is straight and thick, it must therefore be stronger. However, the strength of the polymers is related to their chemical features, their micro-level interactions between molecules. The chemical features of the polymers play a significant role in their mechanical strength. A cis- conformation polymer will have steric hindrance, so the structure will be less decisive than trans-conformation, and so will be less strong. The interesting point emerging here is that the student saw the chemical structure as ‘aligned beads’ and did not consider the chemical interactions or electromagnetic interactions such as repulsion or attraction.

In the second example, a similar way of thinking can be seen. The assumption of ‘the closer the elements are, the stronger they are’ emerged from the response. The second law of thermodynamics states that the entropy of an isolated system never decreases, as isolated systems spontaneously evolve towards thermodynamic equilibrium. One can restate the second law of thermodynamics as that for an isolated system the entropy is maximized and the total energy is minimized at equilibrium. Usually trans- isomers of polymers are more stable than cis- isomers of polymers as their entropy is higher than in cis- isomers. That kind of complex thinking was not employed by those students who gave responses showing some evidence of misunderstanding.

Other wrong statements were mainly again related to the idea of steric hindrance in polymers. In answering this question, many students struggled to detect the steric hindrance effect in the polymer. An example of such responses is:

Cis- conformation is more brittle as in trans- there is steric hindrance of molecules …

Nevertheless, cis- conformations have more steric effect than trans- conformations as in cis- conformations groups are closer in space compared with trans- conformations. So in general, cis- conformations are chemically more unstable and react more easily compared with trans-conformations.

Figure 5.6 shows the frequencies of the responses given by the students.

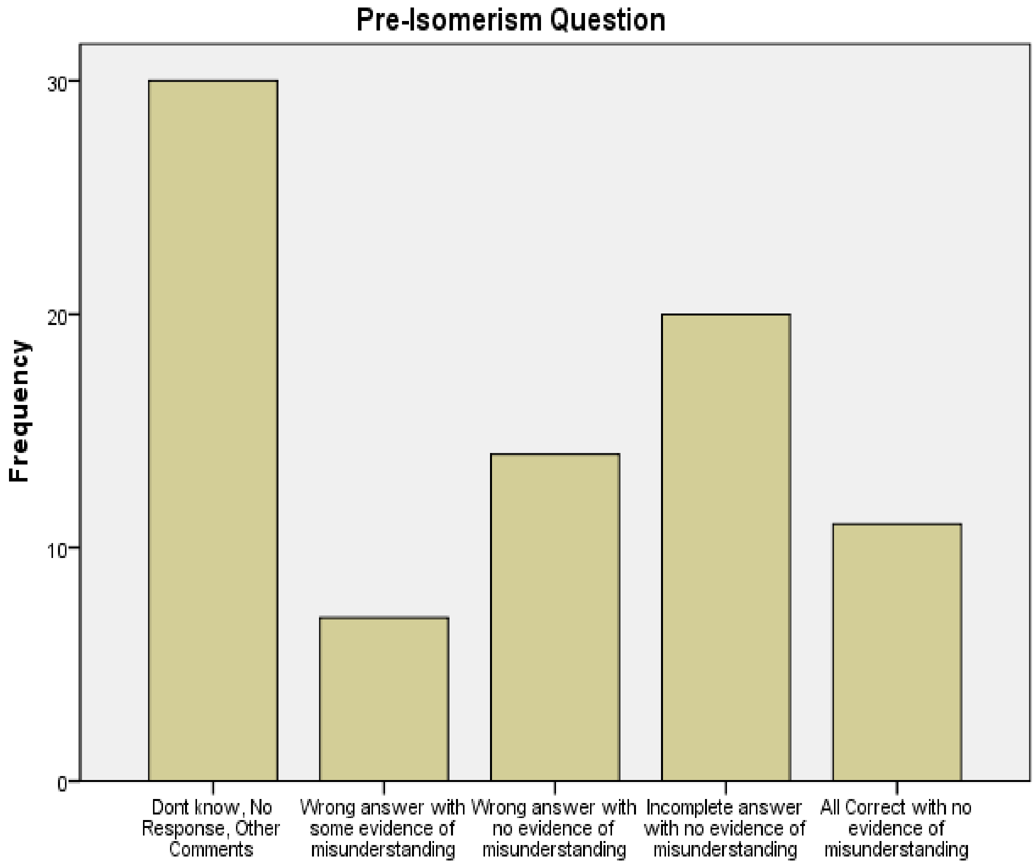


Figure 5.6: The Frequencies of the Responses to the Isomerisation Question

7) Kevlar Question

Kevlar is a broadly-used polymer in different industries mainly due to its fascinating physical features. Kevlar, on an equal weight basis, is almost five times stronger than steel. Obviously the chemical structure of the polymer is the reason for that feature. In this question, the students were asked to explain the strength of Kevlar using their chemistry knowledge.

Pre-Kevlar Question

Code		Frequency	Percent	Valid Percent	Cumulative Percent
D	Don't know, No Response, Other Comments	20	24.4	24.4	24.4
C2	Wrong answer with some evidence of misunderstanding	3	3.7	3.7	28.0
C1	Wrong answer with no evidence of misunderstanding	15	18.3	18.3	46.3
B1	Incomplete answer with no evidence of misunderstanding	18	22.0	22.0	68.3
A1	All Correct with no evidence of misunderstanding	26	31.7	31.7	100.0
	Total	82	100.0	100.0	

Table 5.11: Pre-Intervention Responses to the Kevlar's Strength Question

Table 5.11 shows the students' responses. Students' understanding of intermolecular bonding in polymers was intended to be measured with this question. As can be seen from the table, almost a third of the students, 31.7%, were able to give a correct answer to this question. For example,

In Kevlar, there are hydrogen bonds between electronegative oxygen atoms and hydrogen atoms between the polymer chains. They create very strong intermolecular attractions which make the polymer very strong.

The main contributory factor to this high figure could be that the Kevlar is a very popular polymer in chemistry due to its unique features and many schools use Kevlar in their practical work during A-level, hence students' familiarity with Kevlar and its chemical features might have led to a better understanding of the chemistry of the polymer.

Another reason might be the fact that hydrogen bonding is a fundamental term to explain many chemical features of macro- or micro-sized molecules. So students' familiarity with hydrogen bonding from other topics may play a role. It is also quite interesting to see that the number of answers with some sign of misunderstanding was quite low for this question. From the responses, it can be claimed that Kevlar has been covered slightly better in the students' previous chemistry education compared with the other polymer examples used in this test. Nevertheless, even in this question almost a third of the students gave a wrong answer.

The most common misunderstanding which emerged from the responses was that some students believed that physical strength and chemical activeness are the same ideas. However, it might be the case that a material which shows great physical strength could be chemically very reactive and likely to react with other substances promptly. Those students usually used the electron delocalisation of the benzene ring which increases the chemical stability and strength of Kevlar as the main reason for the physical strength of the material.

Two benzene rings will delocalize the electrons which what makes the Kevlar stronger than steel.

Table 5.11 shows that five codes were employed for the analysis of this question. However, the dominant codes were A1, B1, C1 and D, whereas the number of C2-coded answers was quite low. The low level of codes with the number 2 suggests that the students' responses did not contain many answers with some sign of misunderstanding.

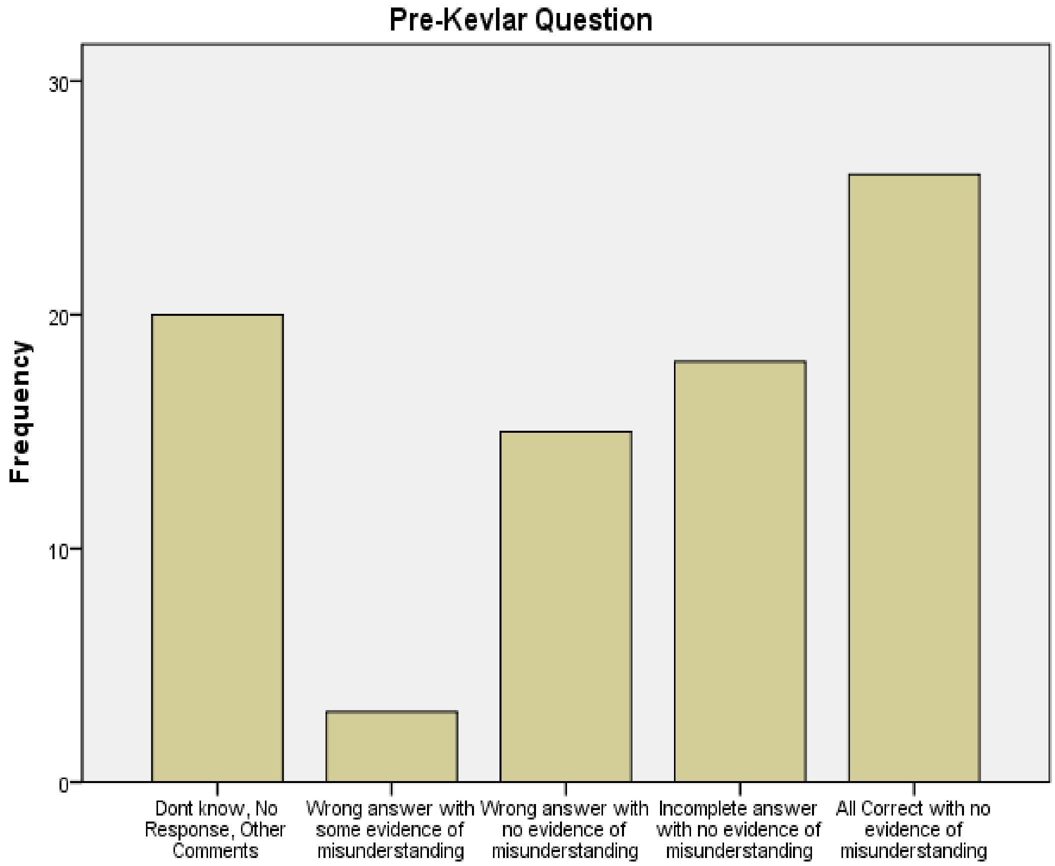


Figure 5.7: The Frequencies of the Responses to the Kevlar's Strength Question

8) Disposal of Kevlar Question

This question probed students' creative thinking by their ability to generate alternative solutions to chemistry-related problems. In this question, the students were asked to suggest an alternative way of disposing of Kevlar. The science curriculum which is taught in educational institutions is seen as presenting a subject that can help to improve the quality of creative thinking among students. Particularly, independent learning strategies in science education are claimed to nourish the creative talents and abilities of students. This question was designed to identify any change in students' ability to think creatively.

Table 5.12 shows that many students were not able to suggest alternative solutions for the problem stated in the question and they struggled to answer the question. The students were asked to create new methods using their previous chemistry knowledge to solve the recycling problems which stem from the chemical structure of Kevlar. Creative thinking has been claimed to be one of the most challenging activities in the cognitive domain. It was put at the top of Bloom's hierarchy of actions in the cognitive domain (Bloom *et al.*, 1956). It might therefore have been too challenging a mission for the students to generate creative solutions.

Pre-Re-use Question

Code		Frequency	Percent	Valid Percent	Cumulative Percent
D	Don't know, No Response, Other Comments	49	59.8	59.8	59.8
C1	Wrong answer with no evidence of misunderstanding	15	18.3	18.3	78.0
A1	All Correct with no evidence of misunderstanding	18	22.0	22.0	100.0
	Total	82	100.0	100.0	

Table 5.12: Pre-Intervention Responses to the Disposal of Kevlar Question

Table 5.12 shows that the predominant code letter used for this question was D, with 59.8% of all responses. The responses clearly show that the students had very limited ability at creating alternative solutions to the problem that they had been given. On the other hand, the number of students who gave a correct answer was almost the same as the number of students who gave an incorrect response. The low response rate to this final question of Test 1 cannot be explained by time limitations as there was no time limitation for completing the questions (although twenty minutes was suggested).

It is very clear from the responses that the majority of the students could not manage to escape from being stuck and devise new possibilities. On the other hand, the students who did manage to provide an answer gave answers with no sign of misunderstanding. An example of the students' answers is

It could be used in less specific applications such as something to shoot at in gun training that needs less of a specific shape, or as protection for people.

Considering that the question asked students to be creative and find their own answers, the responses covered a broad range. Moreover, there was no response detected by the researcher which showed any sign of misunderstanding. The students' ability to generate an alternative solution to problems that they encounter will be discussed on the basis of the results of the students' post-intervention responses of students.

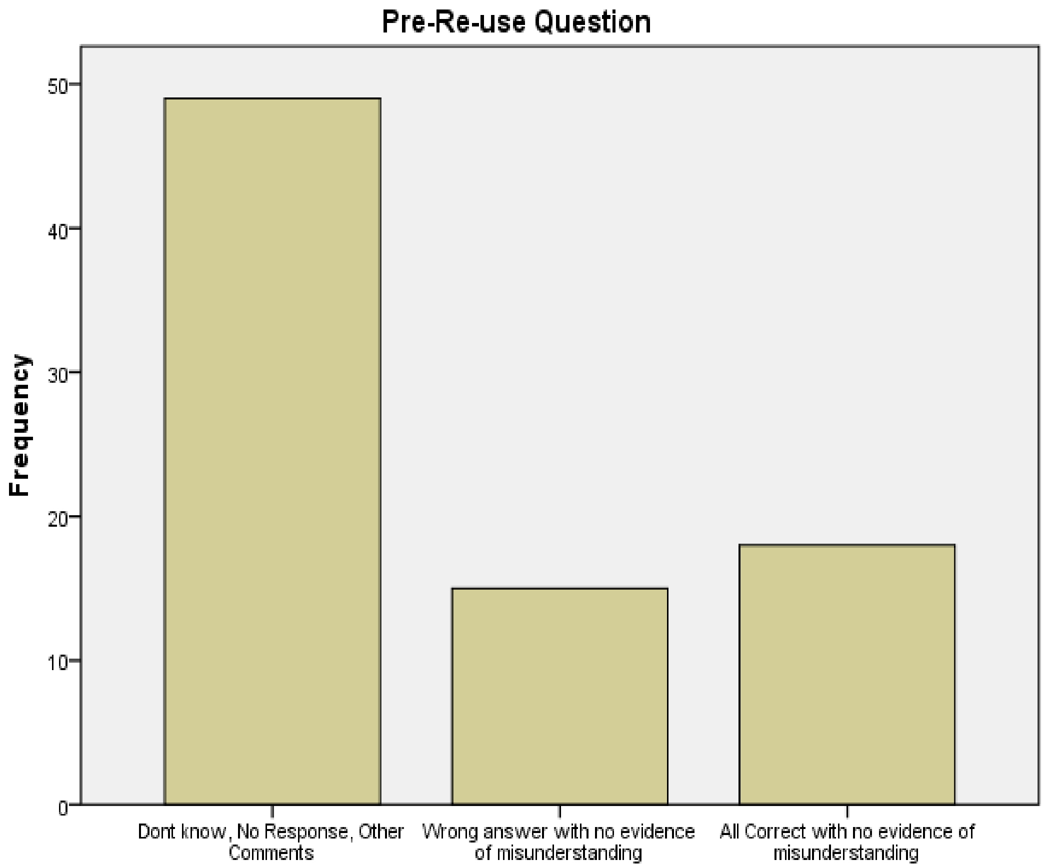


Figure 5.8: The Frequencies of the Responses to the Disposal of Kevlar Question

5.5 Conclusions from the Results of Test 1

In this section, some general conclusions drawn from responses to test 1 will be given.

5.5.1 Some beginning undergraduate chemistry students have some misunderstandings about some of the ideas investigated in this study

Although the percentage, intensity or character of the misunderstandings varied in the responses, the results reveal that some of the students used as a sample in this research study did appear to have misunderstandings about some aspects of polymers. In the next chapter, the researcher will examine the extent to which these misunderstandings were changed as the students progressed through the Macromolecules course.

5.5.2 Some beginning undergraduate chemistry students' creative thinking and scientific reasoning attributes are not very well developed

The *Disposal of Kevlar* and *Combustion* questions were intended to measure students' intellectual attributes on, respectively, generating a creative answer to chemistry problems and judging everyday-life phenomena with scientific reasoning. Students' low success at answering these two questions implies that the abilities which these questions were intended to measure were not very well-developed.

5.5.3 Beginning undergraduate chemistry students seem more successful at recalling knowledge than applying it in different contexts

The students seemed to have memorised definitions of ideas, so they were able to recall that information and write it down in response to a question. However, the majority of them were not able to apply this information to support their argument in different contexts. Since understanding is defined as the ability to apply existing knowledge in a range of novel situations (Darmofal *et al.,* 2002), it can be claimed that students' knowledge levels were relatively higher compared with their levels of understanding about the content of the Macromolecules course. For instance, the *Fashion and Fabrics* question required the students to transfer their knowledge into a novel context. Even though the facts about intermolecular bonding and hydrogen bonding were quite well-known by the students, the structures of the two polymers given (Gore-Tex and nylon) and the relationship between waterproof features and chemical structures were not very familiar to them. They were required to transfer their knowledge of chemistry into a novel context to answer the question correctly; however the majority of them failed to do so.

There are two findings which support this argument this. The students, on average, were more successful in questions which measured their knowledge than in questions which investigated their understanding. Second, the response rate for the questions that were intended to measure students' knowledge was much higher than for the questions intended to measure their understanding of ideas. In those questions, many students failed to give an answer or to support their arguments.

5.6 Test 2

1) Functional Groups Question

Functional groups are groups of atoms found within molecules which are involved in chemical reactions and define the characteristics of those molecules. The understanding of functional groups is essential for understanding the mechanisms of reactions. Because functional groups are the parts of molecules involved in chemical reactions, to be able to detect which part of the molecules are the functional groups is required to understand chemical reactions. This question asked students to detect the functional groups of the polymers given.

Pre-Functional Groups Question

Code		Frequency	Percent	Valid Percent	Cumulative Percent
D	Incomplete answer with no evidence of misunderstanding	44	71.0	71.0	71.0
A1	All Correct with no evidence of misunderstanding	18	29.0	29.0	100.0
	Total	62	100.0	100.0	

Table 5.13: Pre-Intervention Responses to the Functional Groups Question

The first issue which emerges from Table 5.13 is that all the students gave an answer to this question. This implies that they were aware of the importance of functional groups in polymer chemistry and found the question easy. However, possibly more significantly, there was not even one student who gave a totally wrong answer to this question. Every single student was able to recognise at least one functional group from the polymers' structure, and so all were coded B. The possible explanation for that is that some of the functional groups, such as alcohols, aldehydes and ketones, are very familiar to students. Considering the broad use of those functional groups in A-level chemistry as well as in university chemistry courses, the results are not surprising.

On the other hand, what might be considered surprising is the most frequently-given answers category. The code for partially correct with no evidence of misunderstanding was the most employed code for this question, with 53.7% of all the answers. The students managed to estimate the positions of the functional groups of the polymers so they were able to spot where the functional groups were on the molecule structure. However, they were not as successful at naming those functional groups and many students failed particularly with the phosphonic acid group.

PVPA has carboxylic acid and some weird phosphorus thing ...

PCL has ester linkage and PVPA has carboxylic acid and alcohol.

PCL- Carbonyl and Ester, PVPA- Alkane, Carboxylic Acid and Phosphorus.

As can be seen from these three responses, the most challenging part was to name the phosphonic acid group – phosphate or phosphonate were also accepted as correct – and these responses were coded as partially correct. Some students thought that as carboxylic acid groups have a hydroxyl group (–OH), they are alcohols, or that phosphorus as an element itself is the functional group in the polymer. This question was intended to measure students' knowledge acquisition during the Macromolecules course and it did not generate any response with a sign of misunderstanding.

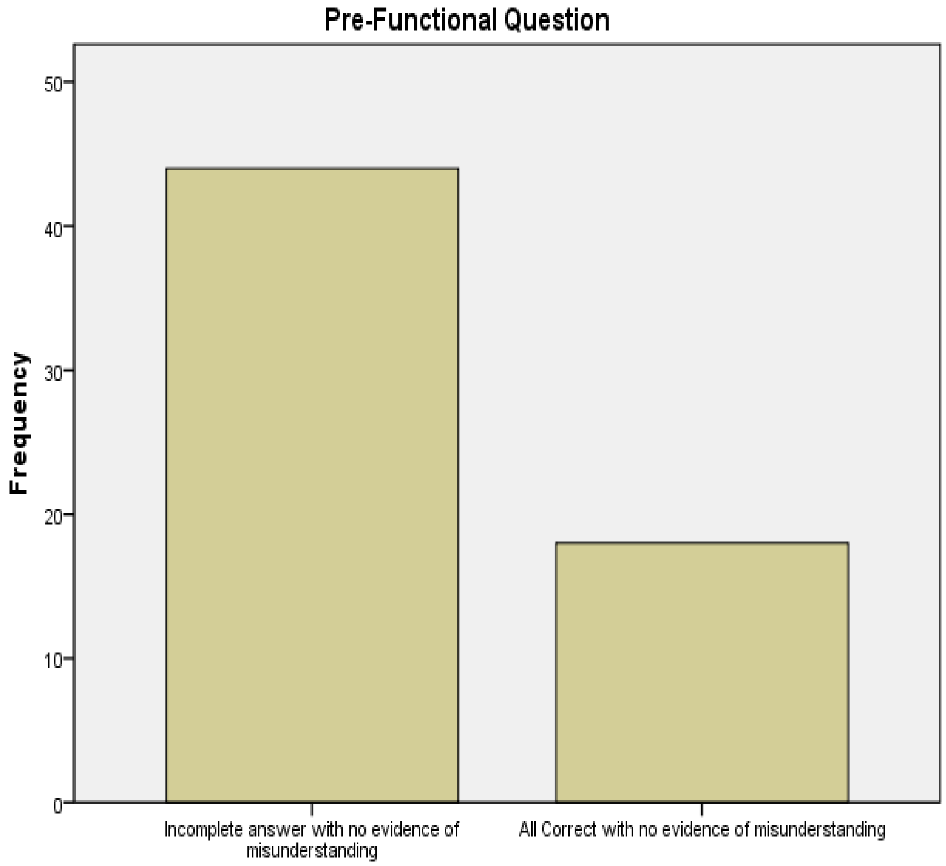


Figure 5.9: The Frequencies of the Responses to the Functional Groups Question

The bar chart comprising Figure 5.9 shows that only two different codes were employed to analyse the responses to this question.

2) Biodegradability and Biocompatibility Question

Biodegradability and biocompatibility are two ideas that are highly emphasized in polymer chemistry, particularly in respect of the use of polymers in medicine. The question investigated students' understanding of these two key ideas. Table 5.14 shows the distribution of the responses in percentages. Almost a quarter of the responses (23.2%) were coded D, which means that the student could not give an answer, and almost another quarter of the responses (20.7%) were coded C, signifying that students gave a wrong answer to the question. The high percentages of those two codes in the pre-intervention test can be explained by the fact that these two ideas were introduced to students very briefly during their A-levels, so a deep understanding of the ideas was not reached. Moreover, biodegradability and biocompatibility are desired features of polymers that are used *in vivo* so they are essential features particularly for current research studies in the domain of medical science.

Pre-Biodegradation

Code		Frequency	Percent	Valid Percent	Cumulative Percent
D	Don't know, No Response, Other Comments	19	30.6	30.6	30.6
C2	Wrong answer with some evidence of misunderstanding	2	3.2	3.2	33.9
C1	Wrong answer with no evidence of misunderstanding	15	24.2	24.2	58.1
B2	Incomplete answer with some evidence of misunderstanding	1	1.6	1.6	59.7
B1	Incomplete answer with no evidence of misunderstanding	20	32.3	32.3	91.9
A1	All Correct with no evidence of misunderstanding	5	8.1	8.1	100.0
	Total	62	100.0		

Table 5.14: Pre-Intervention Responses to the Biodegradability and Biocompatibility Question

As can be seen from Table 5.14, there were responses which showed signs of misunderstanding. Two of them were related to biocompatibility. For instance,

Biocompatible because it is able to form stable bonds within the body.

They are both biocompatible because they have negative oxygen atoms which attracts positive atoms in the body.

The students who gave these answers thought that biocompatibility refers to the bonding of the molecules onto the human body, however, biocompatible materials do not need to be bonded to the human body, and particularly the majority of biocompatible molecules do not bond to other chemical structures in the body.

On the other hand, students' understanding of biodegradability was relatively better. A considerably high number of students were able to realise that weak ester bonds attract water molecules and can be hydrolysed easily in the body. Such as,

… the ester linkage is fairly weak so easy to break with hydrolysis …

… they can be easily broken down with hydrolysis which is suggesting biodegradability and they do not contain any toxic compounds and can stay in the body and can be disposed without harm suggesting they are biocompatible.

The misunderstanding about biodegradability was related to hydrogen bonding. One of the students thought that biodegradability increases with increasing hydrogen bonding, but in fact biodegradability has an inverse ratio with hydrogen bonding. The melting temperature (Tm) of polyesters has a strong effect on the enzymatic degradation of polymers. The higher the Tm, the lower the biodegradation of the polymer, and a high Tm is usually due to the existence of hydrogen bonds (Tokiwa & Suzuki, 1978). One possible reason for this student's explanation is that s/he was confusing the dissolution of polar material with biodegradability. Usually the solubility of polar compounds in polar solvents increases with the existence of hydrogen bonds.

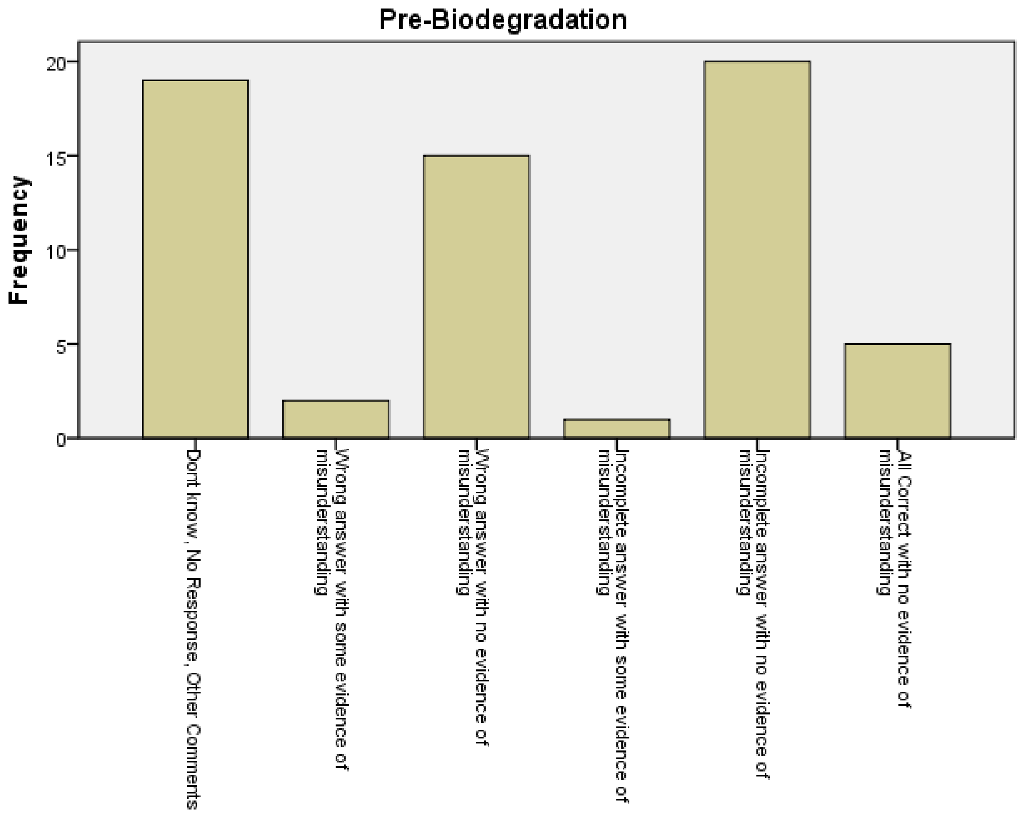


Figure 5.10: The Frequencies of the Responses to the Biodegradability and Biocompatibility Question

3) Chelate Forming Question

This question investigated the students' understanding of chelate formation. Chelate formation is a very significant phenomenon particularly for explaining coordinate bonds. Despite the importance of coordinate bonding, the responses to this question revealed a very low level of understanding of chelate forming.

The explanation for this result may be that coordinate bonds were not very well covered during students' A-level studies. Another possible reason is that the question required a drawing of the possible chelate structure and the students struggled to draw the coordinate bond structures. Some of the notes that students gave to explain their answers suggest that if the question had asked for a verbal explanation, the results might have been slightly better.

Pre-Chelate Question

Code		Frequency	Percent	Valid Percent	Cumulative Percent
D	Don't know, No Response, Other Comments	32	51.6	51.6	51.6
C1	Wrong answer with no evidence of misunderstanding	19	30.6	30.6	82.3
B1	Incomplete answer with no evidence of misunderstanding	5	8.1	8.1	90.3
A1	All Correct with no evidence of misunderstanding	6	9.7	9.7	100.0
	Total	62	100.0		

Table 5.15: Pre-Intervention Responses to the Chelate Forming Question

Since the question came with a relatively long preamble including the description of a chelate and its formation, the students seemed to understand what the question was asking and attempted to answer it accordingly. The majority of the students were able to draw structures of the polymer and put the Ca^{+2} cations in the appropriate places, although they could not manage to draw the coordinate covalent bonds appropriately. Even though the coordinate covalent bond had been introduced to the students during their A-level chemistry courses, they seemed not to comprehend the idea properly.

Another very important point to conclude from the responses is that the students were not careful enough when they were writing chemical structures and their drawings contained many chemical and logical mistakes. There were several examples of oxygen atoms that made more than two bonds, carbon atoms with more than four bonds, open-ended bonds and so on. The importance of molecular structure in chemistry and in science in general is immense. Molecular structure is a basic aspect of scientific literacy and, as future chemists, these students should pay more attention to molecular structures and be able to recognise their importance in the domain. There have been some attempts to show the importance of molecular structure and how significant it is in science, for example a video presentation by Smith (2013).

As can be seen clearly from Figure 5.11, the highest frequencies belonged to C- and D-coded responses. The C-coded responses were mainly from students who could not manage to draw the coordinate covalent bonds between PVPA and calcium ions.

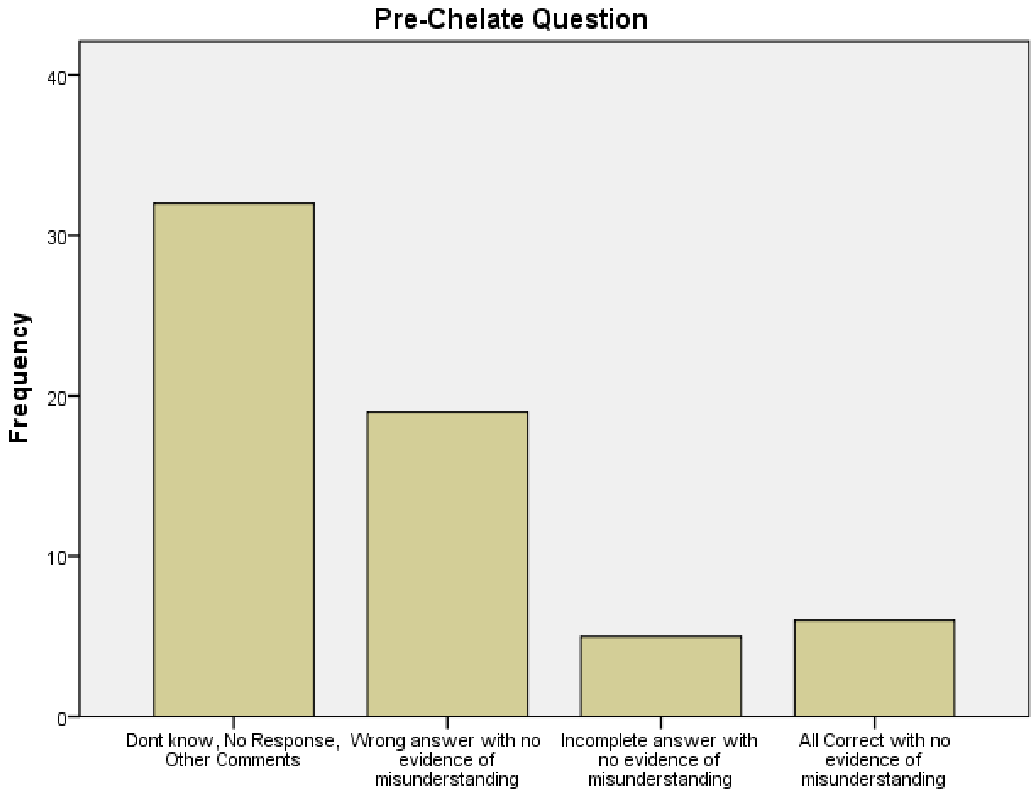


Figure 5.11: The Frequencies of the Responses to the Chelate Forming Question

4) Wettability of Polymers Question

This question was very similar to the *Combustion* question in Test 1 and it was intended to measure students' scientific reasoning by asking them to explain a specific phenomenon, the wetting of polymers.

Table 5.16 shows the spread of students' responses to this question. The most striking result of the analysis of the responses to the wettability of materials question was that there was no response which was coded with the number 2. This means that none of the responses was regarded as showing a misunderstanding of the idea.

Almost half of the students, 41.5% of them, were not able to give an answer to this question in the pre-intervention test. However, among the answers which were given, the researcher did not encounter any which showed any misunderstanding.

Pre-Wettability Question

Code		Frequency	Percent	Valid Percent	Cumulative Percent
D	Don't know, No Response, Other Comments	34	54.8	54.8	54.8
C1	Wrong answer with no evidence of misunderstanding	9	14.5	14.5	69.4
B1	Incomplete answer with no evidence of misunderstanding	3	4.8	4.8	74.2
A1	All Correct with no evidence of misunderstanding	16	25.8	25.8	100.0
	Total	82	100.0		

Table 5.16: Pre-Intervention Responses to the Wettability of Polymers Question

The key issue that was explored in the question was the students' use of reasoning.

The majority of students who gave a wrong answer used their everyday life experiences to explain the wetting phenomenon. For example,

If the water comes from a bigger angle, it gets wet easier.

Students who managed to give a correct answer, on the other hand, were able to offer scientific explanations. An example of a response coded as A1 is that,

Functional groups on PVLA have greater differences in electronegativity such as the hydroxyls on carboxylic acid group compared to the carbonyl group in PCL. This large difference in electronegativity between the oxygen and hydrogen in molecules allow stronger interaction between those molecules and the polar water molecules to form hydrogen bonds. More hydrogen bonds decrease the contact angle and increase the wettability.

Figure 5.12 shows that there was no response coded as showing a sign of misunderstanding.

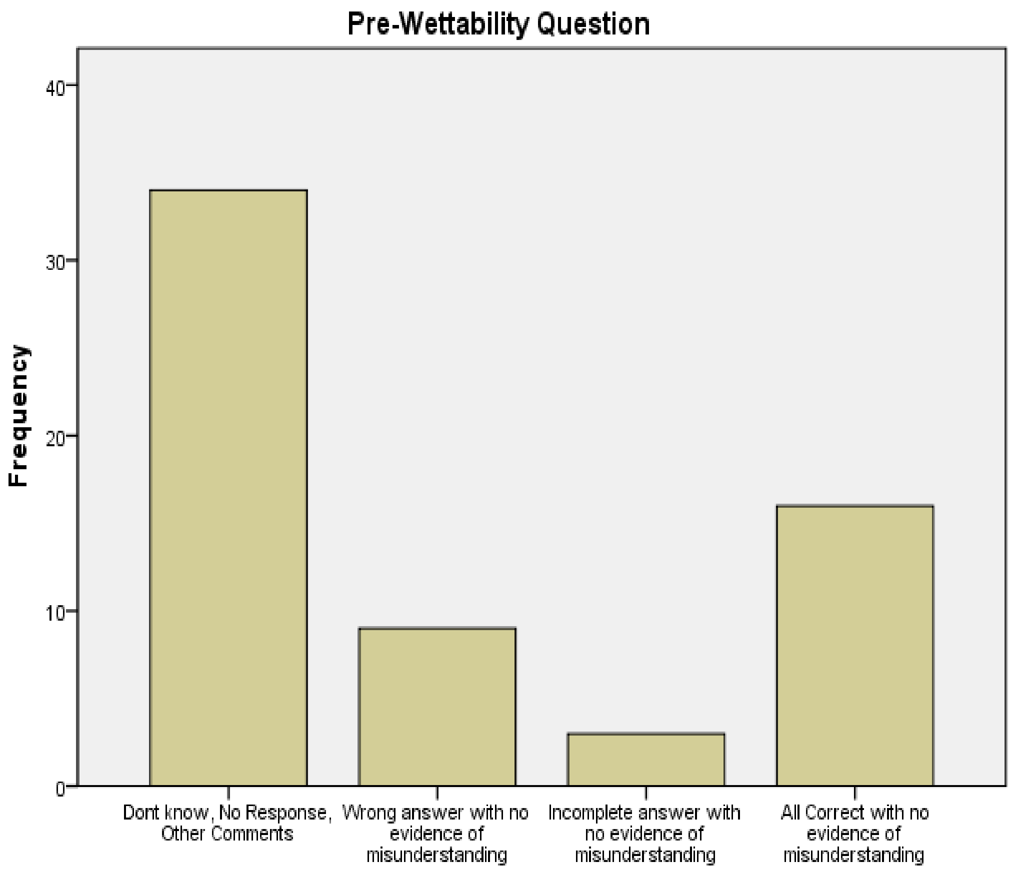


Figure5.12: The Frequencies of the Responses to the Wettability of Polymers Question

5) Mechanical Strength Question

The question on the mechanical strength of PVPA/PCL investigated students' understanding of hydrogen bonds and the relationship between the physical features of a polymer and the existence of hydrogen bonds in polymers.

Regarding the fact that the question investigated a common key idea not only in polymer chemistry but also in many other sub-subjects of chemistry including organic chemistry, the percentage of correct answers was relatively high.

Pre-Mechanical Strength Question

Code		Frequency	Percent	Valid Percent	Cumulative Percent
D	Don't know, No Response, Other Comments	23	37.1	37.1	37.1
C1	Wrong answer with no evidence of misunderstanding	19	30.6	30.6	67.7
B1	Incomplete answer with no evidence of misunderstanding	4	6.5	6.5	74.2
A1	All Correct with no evidence of misunderstanding	16	25.8	25.8	100.0
	Total	62	100.0		

Table 5.17: Pre-Intervention Responses to the Mechanical Strength of PVPA/PCL Question

Wrong answers were mainly a consequence of misreading the table which gave information about the compressive strength of the materials. Some of the students misinterpreted the numbers and thought that a low level of compressive strength meant a high level of durability.

Figure 5.13 shows the frequencies of the responses to the question. There were no signs of misunderstanding. The results clearly show that the students' understanding of hydrogen bonds was quite satisfactory. One reason for this high level of understanding might be the fact that hydrogen bonding is an idea which is covered in variety of contexts during students' A-level chemistry education.

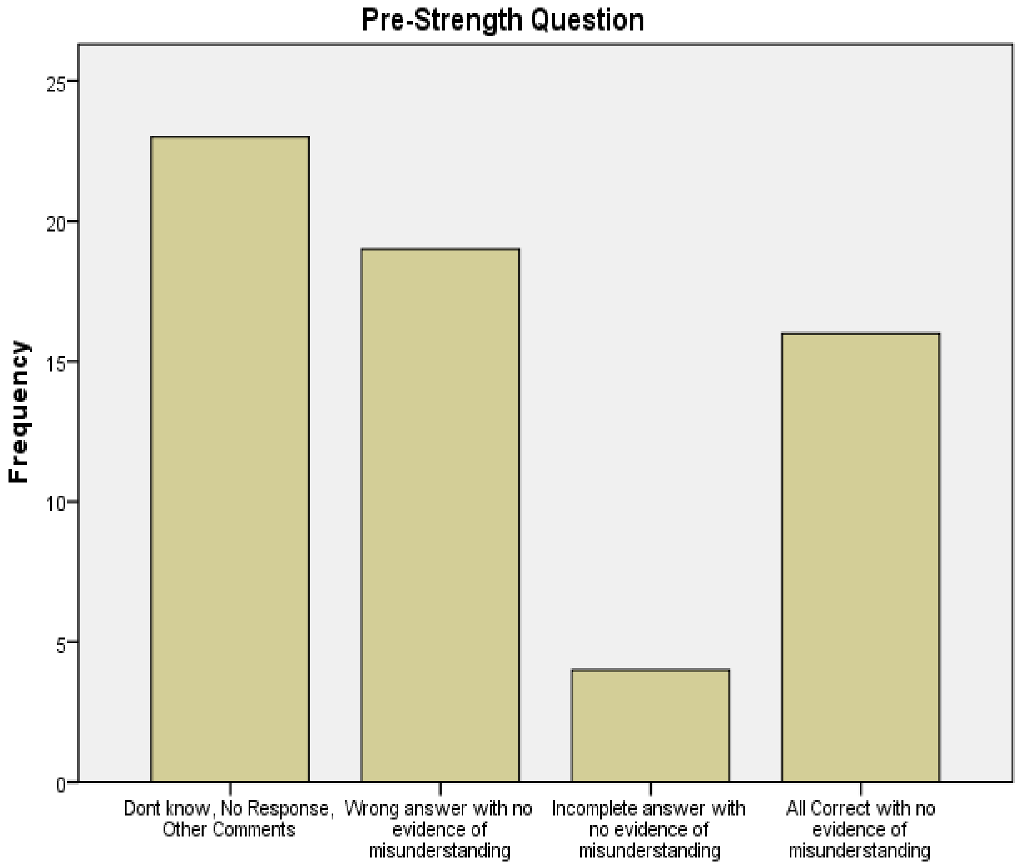


Figure 5.13: The Frequencies of the Responses to the Mechanical Strength Question

6) Calculation Question

This question investigated students' self-assessment abilities before and after the instruction strategy investigated. In order to do this, the students were required to carry out a calculation in the context of polymer chemistry. All the required formulas and values were given in the question except for some unit conversions. If a student were to omit the unit conversion, s/he would reach an absurd result. It was expected that the absurdity of the result would make the student go back and check the calculations again.

An important point which emerged was that compared with other items in the test, the percentage of the responses coded D was quite low. So the majority of the students attempted to give an answer to this question.

Pre-Calculation Question

Code		Frequency	Percent	Valid Percent	Cumulative Percent
D	Don't know, No Response, Other Comments	8	12.9	12.9	12.9
C1	Wrong answer with no evidence of misunderstanding	15	24.2	24.2	37.1
B1	Incomplete answer with no evidence of misunderstanding	31	50.0	50.0	87.1
A1	All Correct with no evidence of misunderstanding	8	12.9	12.9	100.0
	Total	62	100.0		

Table 5.18: Pre-Intervention Responses to the Life Guarantee of PVC Question

On the other hand, the most frequent responses were incomplete answers with no evidence of misunderstanding. Although the majority of the students felt confident enough to give an answer to the question, they could not manage to provide completely correct answers. The main problem which the students had seemed to be the unit conversion, as a large number of them failed to do sensible unit conversions to reach a sensible result as the solution of the question. Most of the answers showed a calculation, suggesting that the students were able to use the related information from the question. However, the values obtained were either far too small or far too big. This suggests that these students carried out the method but did not think about whether the answers which they obtained were sensible. The most problematic unit conversion appeared to be the conversion of molecules to moles. On the other hand, conversion of metres to nanometres was managed by the students more successfully. The explanation for this result may be the frequent use of length conversion units in other courses and subjects. The conversion of molecules to moles, on the other hand, is a chemistry-specific conversion and appeared to be the more challenging one for the students.

Another point worth mentioning is that the students struggled to discuss their results. The question asked them to calculate their results and then discuss their findings in terms of a lifetime guarantee of PVC pipes. As many students failed to make the required unit conversions, their results were unrealistically massive numbers compared with the number that they were supposed to reach. That situation did not seem to make them realise their mistakes in the calculation and go back and check their results again.

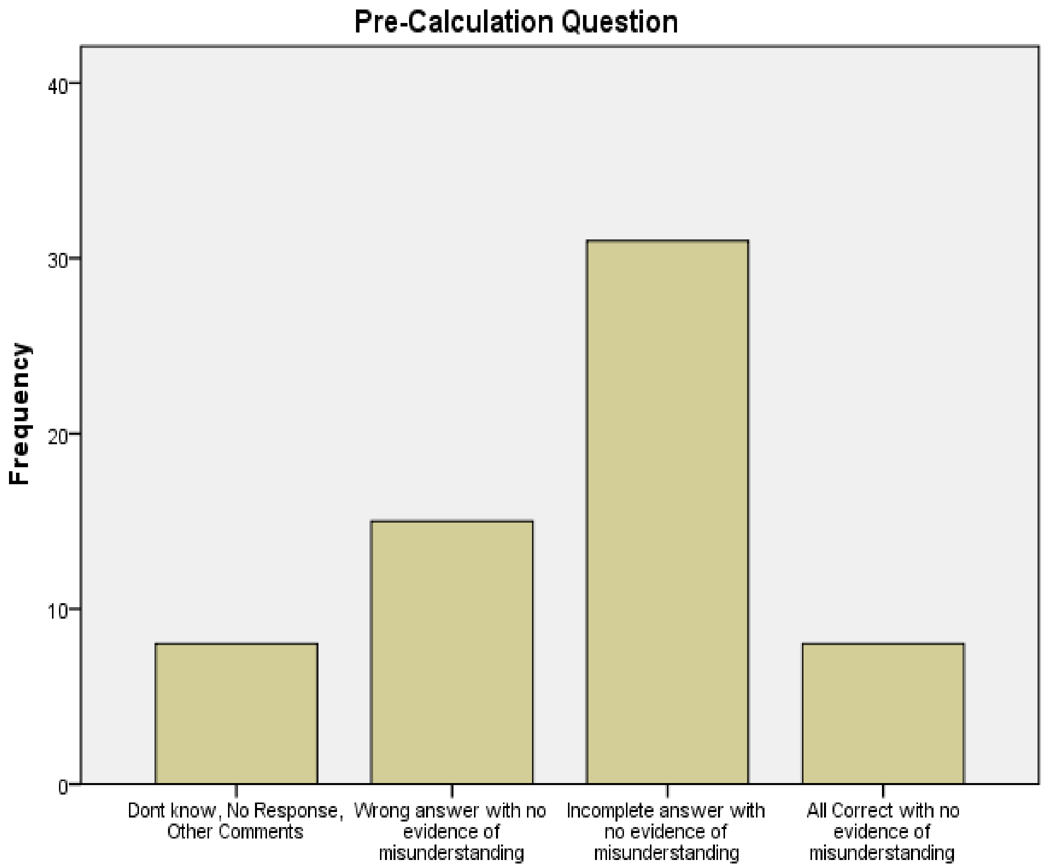


Figure 5.14: The Frequency of Responses to the Life Guarantee of PVC Question

Figure 5.14 presents the frequencies of the answers to this question. As can be seen, the frequencies of two codes (B1 and C1) are relatively high compared with other responses. The expected change in the results of the post-intervention analysis will be a shift towards all-correct answers with no evidence of misunderstanding, which will be regarded as a demonstration of students' improvement in self-assessment ability.

7) Polarity Question

This question was one of the questions in the test which was designed to investigate students' understanding of the idea of polarity and the impact of this idea on the features of polymers.

As can be seen from Table 5.19, the students' responses were spread over a wide range and all-correct answers with no evidence of misunderstanding had the highest percentage at 34.1%. This result is also one of the highest percentages of A1-coded answers among all the questions. This suggests that the students' understanding of the idea of polarity was relatively high compared with the other ideas investigated in the test.

Pre-Polarity Question

Code		Frequency	Percent	Valid Percent	Cumulative Percent
D	Don't know, No Response, Other Comments	12	19.4	19.4	19.4
C2	Wrong answer with some evidence of misunderstanding	2	3.2	3.2	22.6
C1	Wrong answer with no evidence of misunderstanding	13	21.0	21.0	43.5
B2	Incomplete answer with some evidence of misunderstanding	2	3.2	3.2	46.8
B1	Incomplete answer with no evidence of misunderstanding	5	8.1	8.1	54.8
A1	All Correct with no evidence of misunderstanding	28	45.2	45.2	100.0
	Total	62	100.0		

Table 5.19: Pre-Intervention Responses to the Polarity Question

One example of the most common responses to this question is,

Neoprene has a chlorine atom which is very electronegative and makes the molecule and the polymer polar. Neoprene for the fuel line, because the petrol is non-polar it will not solvate the polymer. Isoprene for the brake fluid pipe, the brake fluid is polar so using a non-polar material means the brake fluid will not solvate the pipe.

One common misunderstanding which emerged from the responses was that some of the students thought that isoprene is a polar polymer as it was formed from two different atoms, carbon and hydrogen. However, the majority of the students were able to recognise the very low difference in electronegativity. On Pauling's scale, C has 2.55 and H has 2.2 in electronegativity, so the electronegativity difference is 0.35, which is generally omitted. So the bond between carbon and hydrogen atoms is accepted as a non-polar bond. Moreover, to judge one molecule's polarity, its geometric structure should be taken into account. One example of an incorrect answer is that,

I could use either, as both of the polymers have different atoms and they are polar.

In other responses, some of the students thought that combining polar materials with polar materials and non-polar materials with non-polar materials would increase the compatibility. Their ignorance about the interaction between two materials led students to give wrong answers. For instance,

I would use neoprene for brake fluid pipe cause they are both polar and isoprene for fuel pipe as they are both non-polar, that will be compatible.

Even though the required information about solubility was given in the preamble of the question, it was clearly ignored by some students.

Figure 5.15 presents the frequencies of the responses and the relative dominance of all-correct answers with no evidence of misunderstanding can be seen clearly.

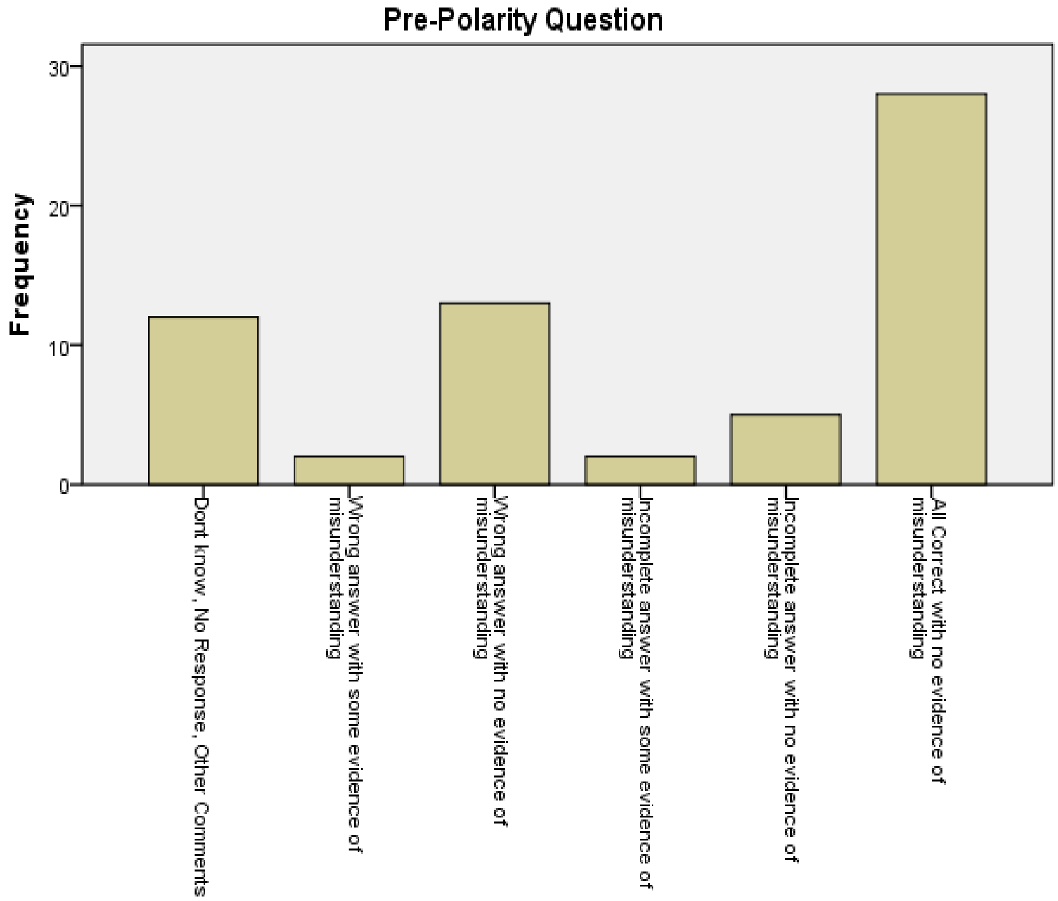


Figure 5.15: The Frequencies of Responses to the Polarity Question

8) Contact Lenses' Structure Question

This question was intended to measure the students' ability to transfer their knowledge to different contexts. They were given two polymers which were very unfamiliar to their A-level knowledge, but they were asked to explain the structure-property relationships, and the only difference between the structures of the two polymers was their functional groups. However, considering the relatively complex structure of the polymers used in the question, the expectations for the response rate to this question were quite low, especially for the pre-intervention phase.

Pre-Lenses' Structure Question

Code		Frequency	Percent	Valid Percent	Cumulative Percent
D	Don't know, No Response, Other Comments	43	69.4	69.4	69.4
C1	Wrong answer with no evidence of misunderstanding	3	4.8	4.8	74.2
B1	Incomplete answer with no evidence of misunderstanding	9	14.5	14.5	88.7
A1	All Correct with no evidence of misunderstanding	7	11.3	11.3	100.0
	Total	62	100.0		

Table 5.20: Pre-Intervention Responses to the Contact Lenses' Structure Question

In this question, two methacrylate-based polymers were given and the students were asked to discuss their different behaviours. This question did not generate very rich data in the pre-intervention phase as the majority of the students were not able to give an answer to the question.

It can be seen from Figure 5.16 that the highest frequency belonged to the D-coded responses. The more challenging structure of the question was expected to allow monitoring of the differences in the understanding of better-engaged students.

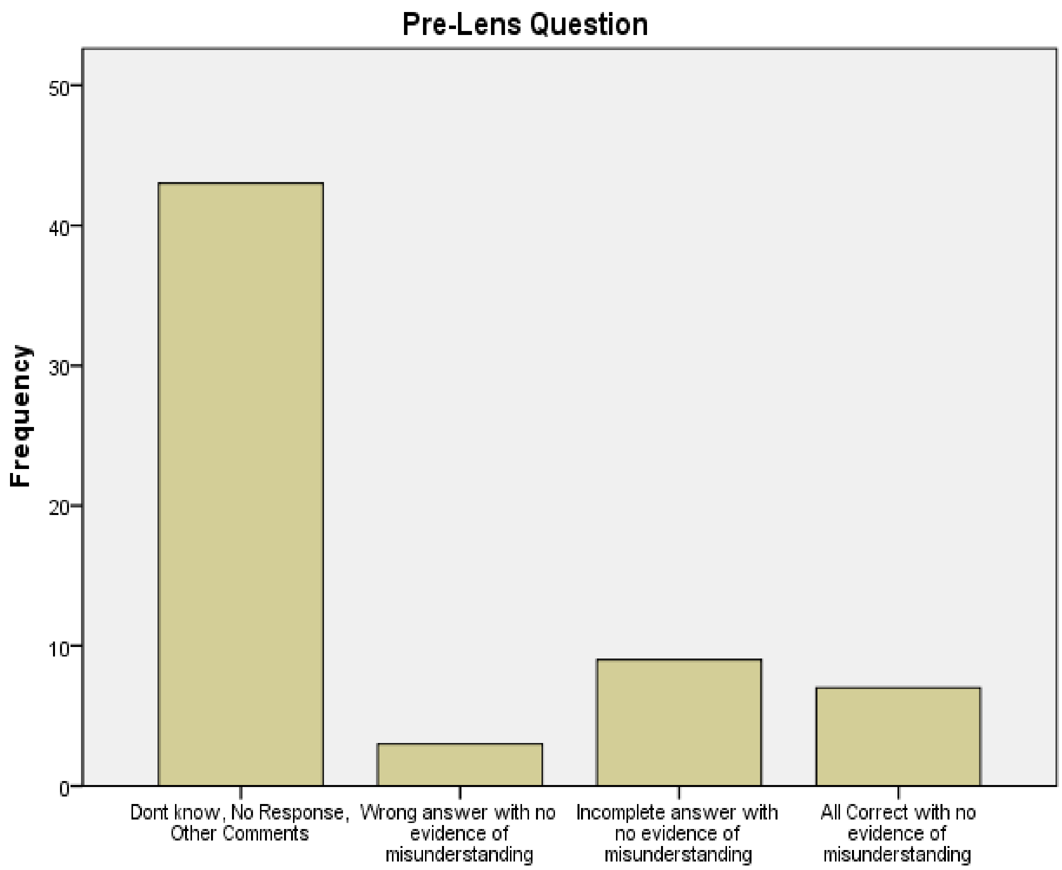


Figure 5.16: The Frequencies of Responses to the Contact Lenses' Structure Question

The most likely explanation of the result is that the two polymers used in the question were relatively more complex-structured polymers compared with the polymers that had been used in the A-level chemistry syllabus, so the majority of the students could not give an answer. Nevertheless, the complex structures of the two polymers would become much simpler if the students were able to recognise the common part of the two polymers (the methacrylate part). Students who managed to give a correct answer to the question were those who recognised that common body in the polymers' structure. For example,

Both have methacrylate structure so the difference in behaviours should be because of the other parts. Poly hydroxyethyl methacrylate has alcohol functional group which would react with water and make it softer?

The student who gave this answer realised the difference in the structures of the two polymers and attempted to give a logical explanation.

5.7 Conclusions from the Results of Test 2

In this section, the researcher will present some general conclusions drawn from the responses to Test 2.

The same conclusions which were drawn from the responses to Test 1 have been supported by the results from Test 2. The students seemed able to recall information about the ideas of *functional groups*, *biodegradability* and *biocompatibility* in the respective questions, but appeared to have problems giving explanations about these ideas. They failed to transfer their chemistry knowledge when they were confronted with a novel situation in the *Contact Lenses* Question. The hydrogen bonding was relatively better understood idea as the results of the *Mechanical Strength* question shows. The responses to the *Wettability* question showed students' lack of scientific reasoning, since they could not transfer data from real world to models' world and *vice versa*. Beginning undergraduate chemistry students have some gaps in their knowledge and understanding of polymer chemistry. Some of the beginning undergraduate chemistry students who participated in this study had misunderstandings about some of the ideas investigated in Test 2. The same arguments that were discussed at the end of the presentation of the analysis of the responses to Test 1 can be applied here.

The responses to Test 2 show that conclusions drawn from the results from Test 1 were reliable, as similar responses have been collected to totally different questions.

5.7.1. The majority of the students struggled to show their self-assessment ability

In addition to the points discussed above, Test 2 revealed another point. As the responses to the *Calculation* question show, many students offered chemically ridiculous solutions to their mathematical calculations, such as offering a guarantee of 1.95×10^{-19} years for PVC polymer. Rather than being doubtful about a clearly impossible calculation and checking it again, they seemed to prefer to offer an explanation which made no sense at all. This suggests that these students carried out the method mechanically, but did not think about whether the answers which they obtained were sensible. That result might be a consequence of a less-developed metacognitive ability of self-assessment. In the next chapter, the researcher is going to attempt to monitor the extent to which those conclusions changed as the students' progressed through the Macromolecules course.

Chapter 6: Differences Monitored between Pre-Intervention Results and Post-Intervention Results

Introduction

In the previous chapter, the students' responses to the diagnostic questions prior to the Macromolecules course were reported in detail. In this chapter, the changes which occurred in the students' responses after they had completed the course are reported, together with possible reasons for the changes in their answers.

6.1 Number of Students

The entire sample reported in the previous chapter, 144 students, started the Macromolecules course and all of them completed the course. As described in the methodology chapter (section 4.6), post-test papers were administered during tutorials on 24 April 2012. Because students were asked to complete the tests during their tutorials, the expected loss in the number of students who completed the second test was minimal. As can be seen from Tables 6.1 and 6.2, all of the students participated by providing responses for the post-intervention data collection and in total 144 tests were collected after the Macromolecules course.

		Post-Recycling Question	Post-LDPE, HDPE Question	Post-Combustion Question	Post-PIC Question	Post-Fashion and Fabrics Question	Post-Isomerism Question	Post-Kevlar's Strength Question	Post-Reuse of Kevlar Question
	Valid	82	82	82	82	82	82	82	82
	Missing	0	0	0	0	0	0	0	0

Table 6. 1:Valid Answers for Test 1

All the papers were collected after the students had finished the final tutorial and students were asked to pick the colour which they had filled in for the pre-test. They were also asked to write down their code which was written on their pre-test to their post-test as well. By this means the anonymity of the students was assured as well as keeping the research variables under control.

		Post-Func. Groups Question	Post-Biodeg. and Biocomp. Question	Post-Chelate Forming Question	Post-Wettability of Materials Question	Post-Mech. Strength Question	Post-Life Guarantee of PVC Question	Post-Polarity Question	Post-Contact Lenses Question
	Valid	62	62	62	62	62	62	62	62
	Missing	0	0	0	0	0	0	0	0

Table 6. 2: Valid Answers for Test 2

As detailed information about the students' backgrounds has been provided in previous chapters, it will not be mentioned again in this chapter.

6.2 Reporting Changed Responses

In this section, the method which was applied to report differences in the students' responses will be explained. First, in order to monitor general differences in students' responses, a paired-sample t-test was used. A paired-sample t-test is used in situations which involve two related observations (that is, two observations per subject) and it reveals whether the means of these two normally distributed interval variables differ from one another. The students' responses were first coded according to the coding chart prepared and then enumerated in order to be transferred to the SPSS programme. This enumeration process is explained in details in section 6.2.1. With the help of the programme, differences between their pre-intervention and post-intervention responses were compared using a paired-sample t-test at the 0.05 level of significance. At this level of significance, there is a possible risk of one in twenty that the result was obtained by chance alone. If the p value is smaller than 0.05, there is a very strong likelihood that an external influence has caused the result, as it is very unlikely that the result was produced by chance alone. The main external influence in this research study that might cause such results was expected to be the instruction strategy of the Macromolecules course, although it would not be realistic to claim that the results were produced by the Macromolecules course itself alone. In this chapter, if a difference is reported as significant, this means that the result was very likely to have been caused by an outside influence such as the instruction method applied in the Macromolecules course.

The second test that was applied to report the results was a chi-square calculation, and this was also calculated at the 0.05 significance level. When the degree of freedom is 1, if χ^2 equals 3.84 or more, this shows that the difference between two groups of data is significant at the 0.05 significance level. The degree of freedom was calculated as 1 because the number of possible outcomes is 2 (responses either coded 1 if there was no sign of misunderstanding or coded 2 if there was some evidence of misunderstanding, as explained in the previous chapter). After the completion of the Macromolecules course, if meaningful learning has occurred, the expected change will be in favour of the answers including fewer or no signs of misunderstanding compared with the pre-intervention results. Students who responded in the first survey by revealing a misunderstanding of an idea may have learned something during the Macromolecules course which led them to respond differently in the second test. As the theoretical explanation of the analysis might be difficult to comprehend, an example calculation will be presented next.

6.2.1 Calculation of the Significance of a Possible Change in Students' Responses

The first statistical analysis was undertaken to monitor the difference in the mean of the answers provided by the students. For this purpose, a paired sample t-test was used. Now, the method applied for measuring the significance in change between the pre- and post-intervention results will be exemplified. Let us assume that the responses of student X to the two tests generated the codes showed in Table 6.3.

In order to transfer this piece of data to the statistical program base, the codes are given values with numbers. A1 is valued as 10, A2 as 9, B1 as 8, B2 as 7, C1 and D coded answers as 6 and C2 as 5. So the answers of student X as transferred to the statistical data base are as shown in Table 6.4.

Pre- Intervention Answers	Post- Intervention Answers
A1	A1
A1	A1
B2	A1
B1	B1
D2	B1
A1	A1
C1	B1
D2	B2

Table 6. 3:Codes of the Example Student's Responses

Pre- Intervention Answers	Post- Intervention Answers
10	10
10	10
7	10
8	8
5	8
10	10
6	8
5	7

Table 6. 4:Numerical Representations of the Example Student's Responses

In this transfer of data, A1-coded answers were accepted as the most valuable responses and C2-coded answers were accepted as the least-valuable responses. As a numerical representation of the 'value' of an answer, this enumeration is a hypothesis. In this hypothesis, A2-coded responses, although they are responses with a sign of misunderstanding, were regarded as more valuable than B1-coded responses. The reason for this is that A2-coded responses were correct answers that included some evidence of misunderstanding about ideas which were not investigated in this case study. Hence, they were accepted as more meritorious than incomplete answers with no evidence of misunderstanding. Wrong answers with an irrelevant response and D-coded answers were valued with the same number, and wrong answers with a sign of misunderstanding were accepted as less valuable than D-coded answers.

After the responses of the entire sample had been transferred to the programme, for each question means were calculated, and the higher the mean meant that the answers were closer to the expected answers. Then, for each relevant question, a paired sample t-test was applied and the significance of the change in the mean was discussed. A positive significant difference meant that a response had become closer to the expected answers and can be interpreted as showing that that student had learned something during the Macromolecules course. In results, standard deviations are also presented. Standard deviation measures the amount of variation or dispersion from the average. A low standard deviation indicates that the data points tend to be very close to the mean. It is important to acknowledge that high standard deviation usually relates to the spread of the results and possibly suggests a low reliability of the instrument.

6.2.2 χ^2 Analysis to Monitor the Change in Students' Misunderstandings

A second statistical analysis was carried out with the intention of measuring any statistically significant change in the students' responses with a sign of misunderstanding. An example calculation is shown as Table 6.5. The results of each question will be discussed under the topics of the questions later in this chapter.

The calculations compared the number of 2-coded responses with the number of 1-coded responses between the pre- and post-intervention tests. Considering the fact that D codes were used for the responses in which the students could not give an answer, they were excluded from the monitoring process of the changes in students' misunderstanding of ideas. The null hypothesis in this chi-square test is that there was no significant difference between the observed and the expected frequencies. The critical value of χ^2, at the 0.05 level of significance when the degree of freedom is 1, is 3.84, and the results are interpreted using that coefficient. So, if our χ^2 value is higher than 3.84, we can reject the null hypothesis and claim that the change in the students' misunderstandings has occurred due to an external impact such as the Macromolecules course itself.

	Pre-Intervention Example Question	**Post-Intervention Example Question**	
Number of 2-coded Responses	29 Expected value=K	12 Expected value=L	41
Number of 1-coded Responses	53 Expected value=M	70 Expected value=N	123
	82	82	164

Table 6. 5:Example Calculation with the Chi-Square Test

$$\chi^2 = \sum((O-E)^2 / E$$

In the formula for the chi-square test, O stands for observed values and E stands for expected values. For the example calculation, the observed values are given in the table, and now the researcher will calculate the expected values.

K= (41x82)/164 = 20.5 M= (123x82)/164 = 61.5

L= (41x82)/164 = 20.5 N= (123x82)/164 = 61.5

$$\chi^2 = \sum((O-E)^2 / E$$

$$\chi^2 = (29-20.5)^2/20.5 + (12-20.5)^2/20.5 + (53-61.5)^2/61.5 + (70-61.5)^2/61.5$$

$$\chi^2 = 3.52+3.52+1.17+1.17= 9.38$$

Since 9.38 > 3.84, the researcher rejects the null hypothesis and the difference is significant. The researcher claims that the change in this student's misunderstandings has been affected by an external impact such as the Macromolecules course itself.

For the rest of this chapter, the differences in students' responses to each question will be discussed using the criteria described above. The questions will be considered in the order used in Chapter 5. A copy of the test can be seen as Appendix 6.

6.3 Test 1

1) Recycling Process Question

The question about the recycling process was a quite straight-forward question probing students' knowledge gain about the recycling process. This piece of knowledge was expected to be covered by students during their independent investigations. Table 6.6 shows the results of the paired sample t-test. Students' were asked to write their knowledge of the importance of the recycling process.

As can be seen from Table 6.6, the p value is greater than 0.05. This shows that the students' knowledge gain about the recycling process was not significant. Looking at the table, it can be seen that students' average mean has slightly increased (0.329), however this increase was not significant at the 0.05 significance level.

		Mean	Mean Difference	Std. Deviation	95% Confidence Interval of the Difference		Sig. (2-tailed) p value
	Pre-Recycling Question - Post-Recycling Question	8.33 8.66	.329	1.920	-.101	.759	.132

Table 6. 6: Results of the T-Test for the Recycling Question

There was an increase in the number of A1-coded responses and there was a decrease in the number of B1-coded responses in the post-intervention data compared with the pre-intervention responses. However, this change was not big enough to create a statistically significant difference. As Figure 6.1 shows, only four codes were used for the analysis.

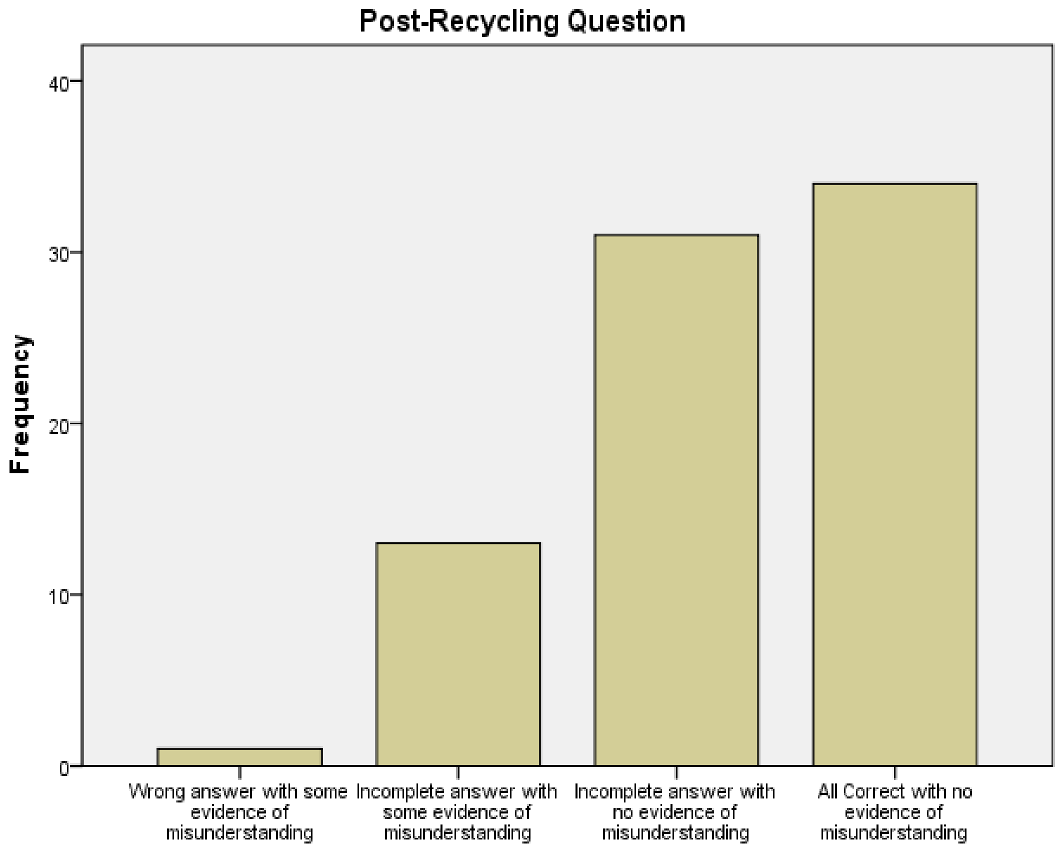


Figure 6. 1: The Frequencies of the Responses to the Recycling Question after the Intervention

In order to monitor any change in the proportion of responses which showed a sign of misunderstanding, a chi-square test was used. The number of responses which showed a sign of misunderstanding had decreased from 21 to 14 after the Macromolecules course. After analysing the students' misunderstandings, the null hypothesis is that the Macromolecules course had little or no effect on students' understanding of the recycling process.

	Pre-Intervention Recycling Question	Post-Intervention Recycling Question	
Number of 2-coded Responses	21	14	35
Number of 1-coded Responses	61	65	126
	82	79	161

Table 6. 7: Chi-Square Test for the Recycling Question

$\chi^2 = 1.49$

Since 1.49 < 3.84, the researcher accepts the null hypothesis and that the change in the number of responses with a sign of misunderstanding is not statistically significant.

Discussion:

As discussed in the previous chapter, quite a high proportion of students had given a correct answer to this question in the pre-intervention analysis. However, there were also some students who had misunderstandings about the recycling idea. Even though there was a decrease observed in students' responses with a sign of misunderstanding after the Macromolecules course, the change was not statistically significant. Students gave responses with same misunderstandings after they had completed the Macromolecules course. The most problematic ideas still seemed to be "*every plastic is made of crude oil*" and *"we can recycle every plastic"*. Furthermore, the difference between re-use and recycling still appeared to be problematic for some students after the Macromolecules course, as it was one of the most frequent misunderstandings for students before the course. These findings have many similarities with the literature about students' understanding of the recycling idea. For example, some students have understanding problems with the distinction between reuse and recycling, or some students have understanding problems about the limitations of recycling (Kortland, 1992). However, one significant difference is about the depletion of raw materials. Kortland (1992), in his comprehensive study on students' understanding of the recycling process, found that the depletion of raw materials was never or rarely mentioned by students. In this current research study, however, this point was mentioned profusely by students. One possible reason for this difference could be the age difference between the two samples as Kortland used younger respondents in his study. So it can be claimed that students' responses to environmental problems get better when they reach higher levels of education. Another reason could be the time difference between the two researches studies as the emphasis on the value of raw materials has increased immensely over the last two decades, with a particularly increased emphasis on the environmental sciences, and this might have increased students' awareness of the significance of raw materials.

2) Branching Question

This question probed students' fundamental understanding of structure-property relationships, particularly branching in the structures of HDPE and LDPE polymers. The improvement in the proximity of the responses to the expected answer is shown in Table 6.8 and the change is not statistically significant at the 0.05 level, suggesting that the students' understanding of the structure-property relationships in HDPE and LDPE polymers had not improved significantly during the Macromolecules course. About 64% of the students at the post-intervention survey offered correct answers to this question. This number is quite high, but the number of correct answers did not change significantly after the Macromolecules course.

		Mean	**Mean Difference**	**Std. Deviation**	**95% Confidence Interval of the Difference**		**Sig. (2-tailed) p value**
	Pre- Branching Question	8.70	.329	2.707	-.277	.935	.283
	Post- Branching Question	9.03					

Table 6. 8: Results of the Paired Sample T-Test for the Branching Question

As can be seen from Table 6.8, the p value is higher than 0.05, which shows that the improvement in students' understanding of the branching idea in HDPE and LDPE polymers during the Macromolecules course was not statistically significant. Some responses implied that the students were more comfortable with the idea that less branching in chemical structures can help polymers to pack closely and increase the possibility of having more and stronger intermolecular bonding. One possible reason for this result could be the fact that whichever application of the polymers received more interest from the students to investigate for their project during the Macromolecules course, they were expected to reference the chemical structures of the polymers that allow polymers to be used in their specific contexts. For example, if students were interested in the polymers that are used in spacecraft, they had to investigate the chemical structure of those particular polymers that give them aerodynamic features, or if they were interested in the polymers used in sports, they needed to investigate the chemical structure of those polymers that give them smooth surface features. All of these features are closely related with the branching of polymers. So the students' understanding of the structure-property relations in polymers was expected to be very high. Moreover, many students were interested in environmental chemistry, and HDPE and LDPE are two common polymers which are widely investigated in environmental chemistry. Considering those points, a significant change in the students' understanding of those relationships was expected after the Macromolecules course; however the post-intervention results reveal that that was not the case.

Figure 6.2 shows the distribution of the responses after the Macromolecules course.

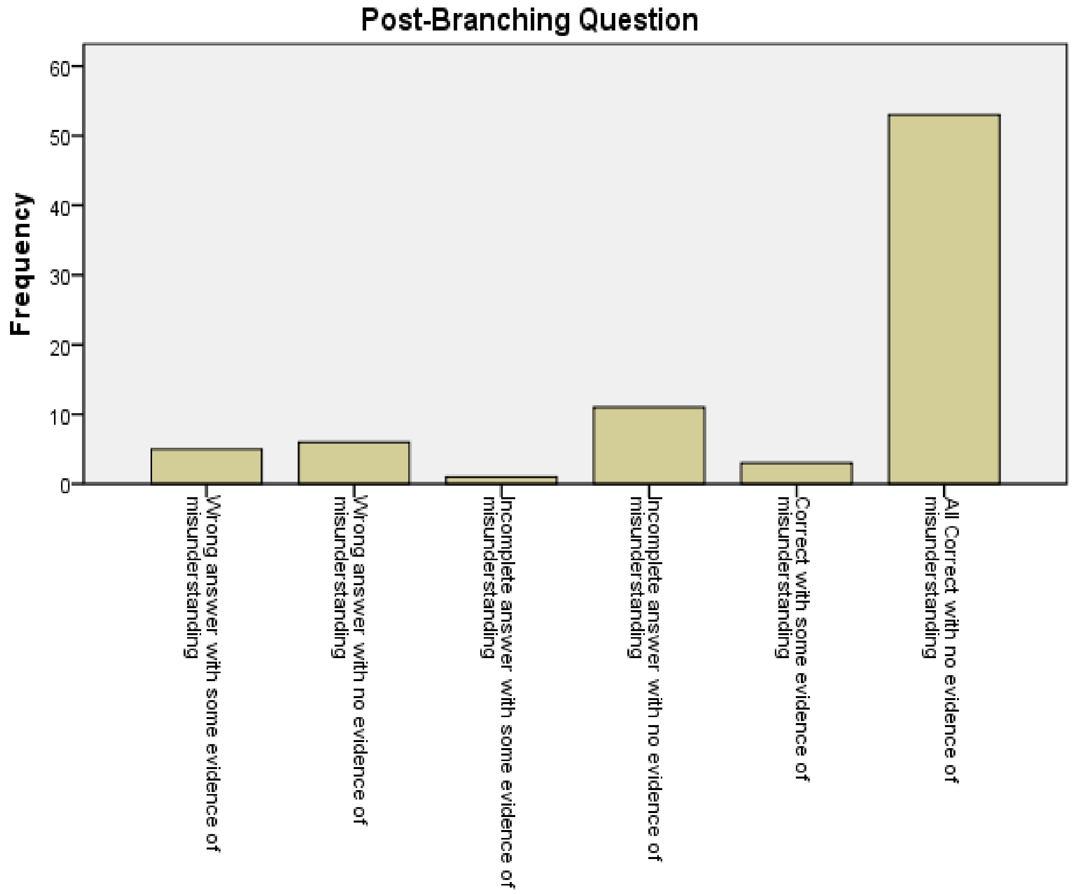


Figure 6. 2: The Frequencies of the Responses to the HDPE and LDPE Structures Question after the Intervention

Table 6.9 shows that the number of answers with a sign of misunderstanding had only decreased by one student. The significance of this chance was calculated using a chi-square test and results are shown in the table.

	Pre-Intervention HDPE and LDPE Question	**Post-Intervention HDPE and LDPE Question**	
Number of 2-coded Responses	11	10	21
Number of 1-coded Responses	71	69	140
	82	79	161

Table 6. 9:Chi-Square Test for the HDPE and LDPE Question

$\chi^2 = 0.08$

Since 0.08 < 3.84, the researcher accepts the null hypothesis and the difference is not significant.

Discussion:

Again in this case, the result suggests that the Macromolecules course had little or no impact on students' understanding of the idea of branching in chemical structures. Even though there was a decrease in the number of responses with a sign of misunderstanding in the post-intervention analysis, this decrease was not significant at the 0.05 level. There were eleven answers with a sign of misunderstanding in the pre-intervention survey results, and this number decreased to ten in the post-intervention survey. It seems that some students still struggled to understand the steric impact of branching that prevents polymers from getting closer, even after their completion of the course.

The most common misunderstanding was that students thought that more branching meant more intermolecular bonding. This is similar to a general intuitive rule (Stavy & Tirosh, 1996) that 'the more of A (the salient quantity), the more of B (the quality in question)'. In the post-intervention analysis, same students still continued to believe this. This finding matches the literature which showed that students transfer and confuse terms from the macroscopic area of matter with the sub-microscopic area of the smallest particles (Barke *et al.*, 2009). In their responses to this question, the students thought that more-branched molecules can interact better with each other, just as at the macro level it would be very possible to expect that the branched parts of materials stick together more easily than the smooth parts of materials. However, this explanation does not correspond to the behaviours of polymers at the molecular level.

3) Combustion Reaction Question

This question was intended to investigate the impact of the independent learning approach on students' scientific reasoning. It was anticipated that the students learn much about combustion reactions through their experiences in life.

The conclusions drawn from those experiences may differ hugely from the information which chemistry teaches to students. Moreover, conclusions drawn from students' everyday life experiences may even be obstacles that can impede understanding of the ideas taught in chemistry courses. This question was intended to monitor the impact of the Macromolecules course on the students' way of interpreting this natural phenomenon which will then be used as a means to judge their scientific reasoning.

First, as can be seen from Table 6.10, the p value is smaller than 0.05, which suggests that some students' way of thinking about combustion reactions had shifted from naïve explanations to more scientific ones.

		Mean	Mean Difference	Std. Deviation	95% Confidence Interval of the Difference		Sig. (2-tailed) p value
	Pre- Combustion Reaction	7.04	.722	2.616	.136	1.308	.016
	Post- Combustion Reaction	7.76					

Table 6. 10: Results of the Paired Sample T-Test for the Combustion Reaction Question

The results show an increase in the proportion of A-coded responses and a decrease in B- and C-coded responses. It can therefore easily be claimed that the number of students who used a scientific approach to explain combustion phenomena had increased in the post-intervention survey. Changes in the responses to the question reflect a positive learning experience during the course.

Figure 6.3 shows that the number of wrong answers decreased. Another notable change is the decrease in the number of D-coded responses. Many students who could not provide an answer in the pre-intervention survey managed to generate an answer in the post-intervention survey.

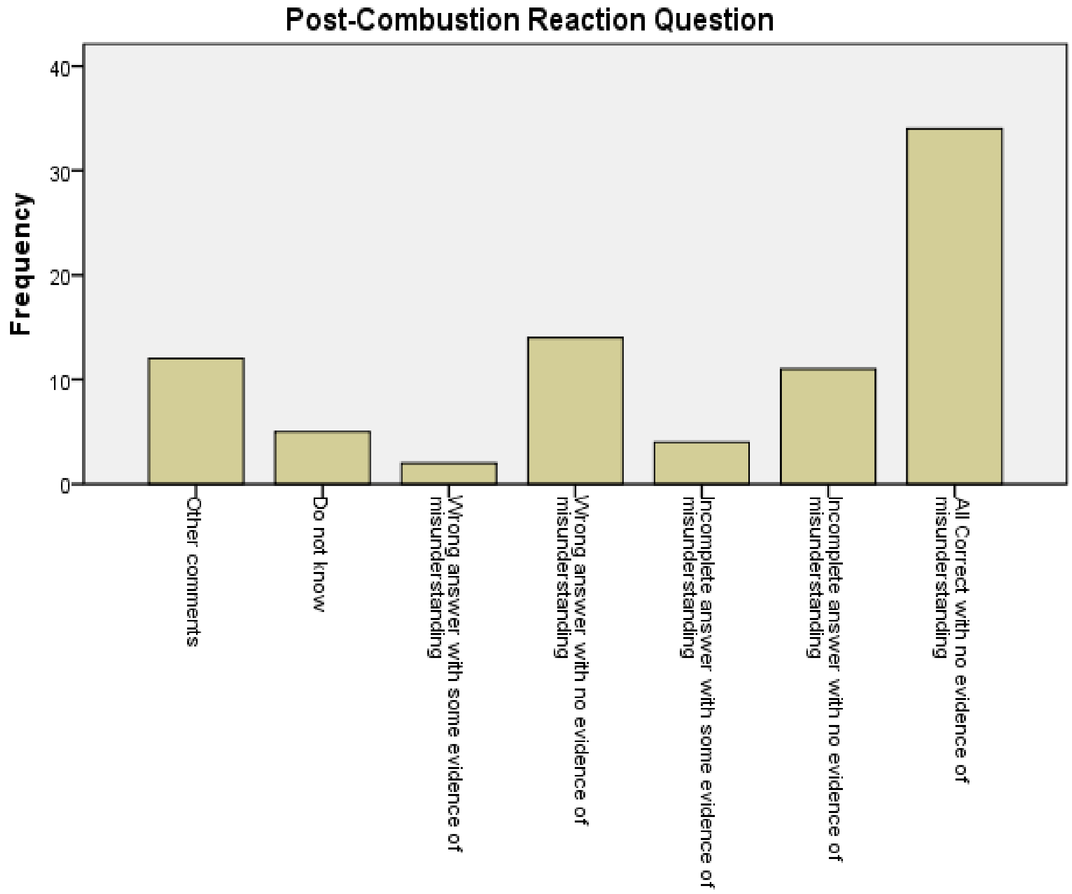


Figure 6. 3: The Frequencies of the Responses to the Combustion Question after the Intervention

In terms of the change in students' misunderstandings, there was no change in the number of responses which showed a sign of misunderstanding before and after the Macromolecules course. There were seven responses in each data collection.

Discussion:

These results suggest that the students had progressed in their thinking from associating the combustion reaction of HDPE and LDPE with their everyday experience of burning plastics to identifying the event as a chemical reaction between HDPE and/or LDPE and oxygen. In some examples of the responses, this shift is illustrated clearly:

Considering they are pure and assuming complete combustion, it would be expected to see nothing as the $CO_{2(g)}$ given off is colourless, and the H_2O would be in its gases state due to the exothermic reaction. This overall leaves nothing to observe. There would be no solid or liquid left in the crucible.

The student who gave this response emphasized the factors that make a chemical combustion reaction different from her/his own everyday life experiences. First, s/he considered the purity of the materials, then stressed the assumption that it is a complete combustion reaction. The variables differ in a chemical explanation from students' everyday life experiences.

Referring to the literature on students' ideas about combustion reactions (Watson *et al.* 1997), it can easily be claimed that the number of students who are chemical reaction thinkers (*see* Section 2.6.3) had increased whilst the numbers of transmutation thinkers and modification thinkers had decreased during the Macromolecules course.

In the post-intervention results, one interesting point was that some students also mentioned the kinetics of the two polymers' combustion reactions. Even though it was not asked in the question, some students attempted to compare the speeds of the two reactions. This may be due to other courses in which the kinetics of reactions are taught – not particularly those two reactions' kinetics, but in general – during the intervention time. Those parts of the students' answers were not included in the assessment as the question was not intended to do so.

In terms of the signs of well-established childhood misunderstandings that had been faced and mentioned in the previous chapter (section 5.4 – Question 3), there was no change observed in the post-intervention results. Answers quoted in Chapter 5 emerged again in a quite similar pattern.

4) Plastic Identification Codes Question

This question was intended to measure students' knowledge acquisition about the everyday life applications of polymers. In this question, the difficulty which appeared in the responses was that the majority of the students had been unable to give a full answer in the pre-intervention analysis. This was a bulleted question and the students were asked to give three different reasons. However, the majority of them were able to provide even one reason in the pre-intervention analysis. After the Macromolecules course, they were expected to be able to give more reasons. The difference between the pre- and post-intervention responses is presented in Table 6.11.

		Mean	Mean Difference	Std. Deviation	95% Confidence Interval of the Difference		Sig. (2-tailed) p value
	Pre- PIC Question	7.95	.203	1.522	-.138	.544	.241
	Post- PIC Question	8.15					

Table 6. 11: Results of the Paired Sample T-Test for the PIC Question

Comparison of the pre- and post-intervention surveys showed a p value greater than 0.05, which shows that the increase in the students' knowledge acquisition about applications of PICs was not statistically significant after the Macromolecules course.

In Figure 6.4 showing the frequencies of the responses, the most significant difference in the responses was the change in responses coded B. There was a slight shift from B-coded responses to A-coded responses. This implies that the students were slightly more competent in their knowledge of PICs. Moreover, one important point is that there was no response in the post-intervention survey that was coded D. This shows that there was no student who could not generate an answer to this question at the post intervention stage. However, these changes were not big enough to create a statistically significant difference.

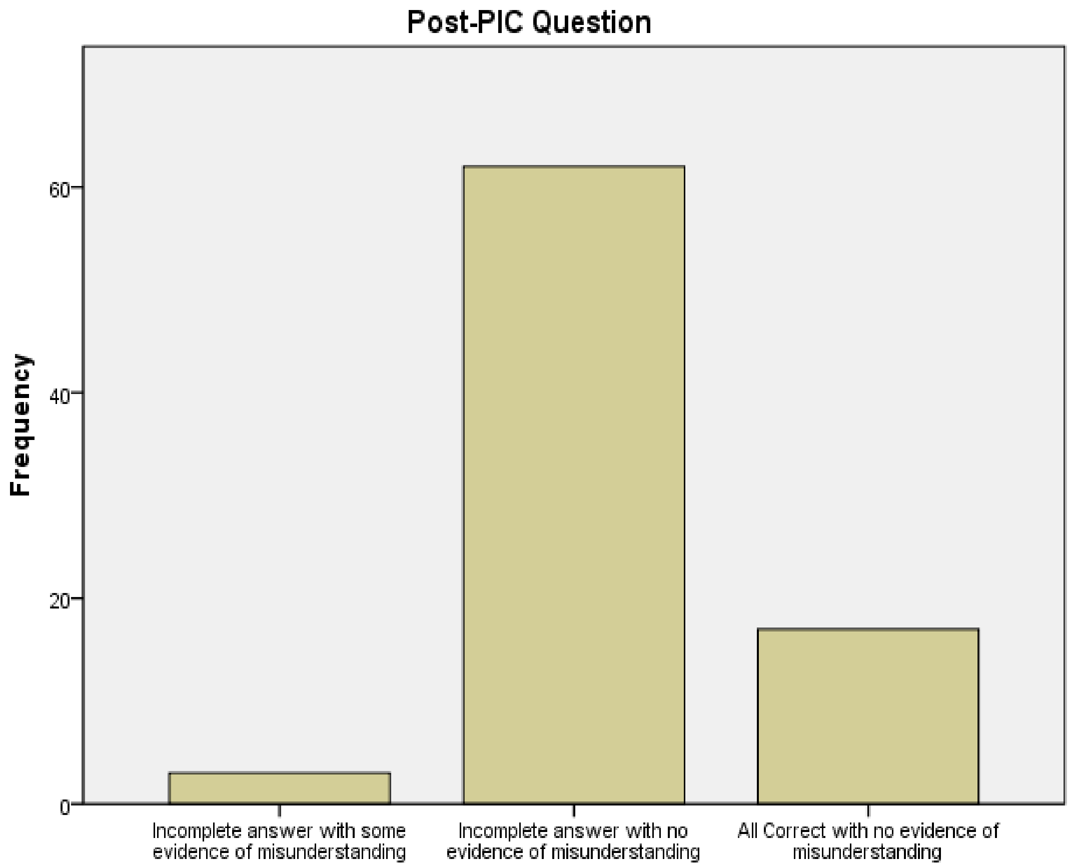


Figure 6. 4: The Frequencies of the Responses to the PIC Question after the Intervention

This question did not generate any response with a sign of misunderstanding before or after the Macromolecules course, so there was no need for chi-square calculations.

Discussion:

Considering that this question was intended to gauge any change in the students' knowledge about the applications of particular polymers in everyday life, the question did not generate responses which reflected deep ideas about the chemistry of polymers. However, the expected improvement for this question was the number of the responses coded A, rather than an improvement in students' understanding of the ideas in chemistry.

The high number of expected answers in both the pre- and post-intervention responses to this question compared with those to the questions which sought to measure students' understanding implies that the students were more successful at recalling a piece of information in the recycling context compared with presenting their understanding of the recycling context or their ability to use that information in different contexts. Although they were relatively more successful at this question compared with the others in both the pre- and post-intervention analysis, there was no statistically significant improvement in their knowledge acquisition during the Macromolecules course.

5) Fashion and Fabrics Question

The Fashion and Fabrics question explored students' understanding of the chemical structures of nylon and PTFE polymers. The improvement, shown in Table 6.12, was statistically not significant at the 0.05 level, suggesting that their ability to transfer knowledge to different contexts was not affected significantly during the Macromolecules course.

		Mean	Mean Difference	Std. Deviation	95% Confidence Interval of the Difference		Sig. (2-tailed) p value
	Pre- Fashion & Fab. Question	6.68	.316	2.222	-.181	.814	.209
	Post- Fashion & Fab Question	7.00					

Table 6. 12: Results of the Paired Sample T-Test for the Fashion and Fabrics Question

The students found this question relatively difficult compared with others in the survey and this is illustrated by the high proportion of persistent D codes; about 22% were coded D in the second survey and the results are presented in Figure 6.5. This indicates that many students were unable to apply their knowledge in the context of the question and they still could not give an answer to the question.

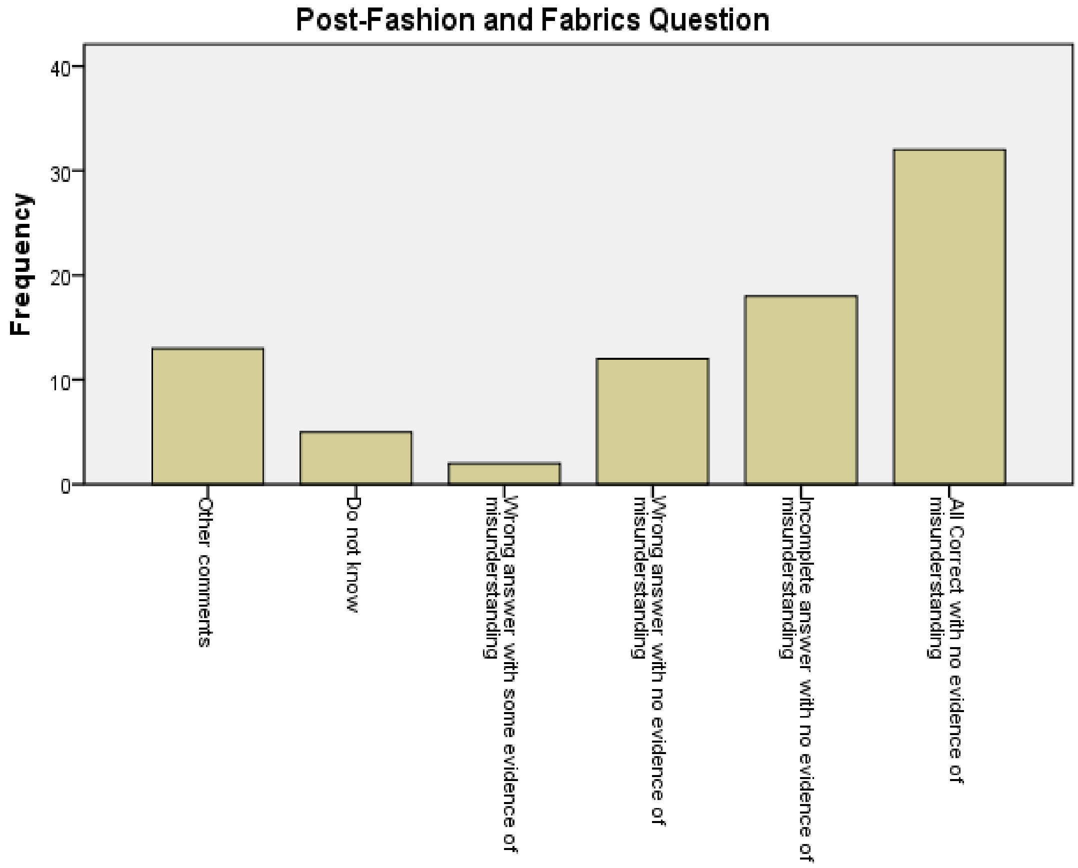


Figure 6. 5: The Frequencies of the Responses to the Fashion and Fabrics Question after the Intervention

In terms of students' misunderstandings, this question generated quite interesting results. In the post-intervention data, there were more responses with a sign of misunderstanding and the chi-square test was applied to see the significance of the change in the number of responses showing misunderstandings. Table 6.13 presents the findings of the chi-square test.

	Pre-Intervention Fashion and Fabrics Question	Post-Intervention Fashion and Fabrics Question	
Number of 2-coded Responses	4	13	17
Number of 1-coded Responses	78	66	144
	82	79	161

Table 6. 13: Chi-Square Test for the Fashion and Fabrics Question

$\chi^2 = 5.76$

Since 5.76 > 3.84, the researcher rejects the null hypothesis and the difference is significant.

Discussion:

To assess the reasons for these findings, the students' responses will be analysed. The most common problem encountered by the students in this question was that they were only able to think about the features of chemical materials at micro level. For instance, they were only able to focus on hydrogen bonds or the electronegativity of atoms.

> *… both substances can easily hydrogen bond with water causing waterproof properties.*

> *... both of them are waterproof as they do not react with water ...*

However, the question asked the students to transfer their thinking from the atomic (micro) level (the water-repellent chemistry of those polymers) to the macro and tangible level (the waterproof and breathable features of the materials). In addition to these two levels, another level that is used in chemistry is the symbolic level. In the literature, there is considerable data which show that students struggle to comprehend and use the convention between those levels (Gabel, 1994; 1998). The reasons for this may vary, such as lack of experience with the macro level (Hodson, 1990; Nelson, 2002), or the existence of misunderstandings about the particulate nature of matters that can impede understanding the nature of the sub-microscopic level (Harrison & Treagust, 2002).

The data gathered from this question support the literature that students have problems converting their thinking between the sub-atomic (micro) and macro levels. Two possible reasons for this result are the students' lack of experience with the macro type and their misunderstandings about the sub-microscopic level of the polymers. First, the polymers used in the question, particularly Gore-Tex (expanded poly (tetra fluoro ethylene)), are not very familiar to students (for the purpose of creating a different context); although most should know about Gore-Tex from their

A-levels. The second possible reason is that the students had misunderstandings at the sub-atomic level which might stem from different reasons. Those misunderstandings prevented them from seeing the scope and limitations of the sub-atomic features of the structures.

Table 6.13 shows that students' misunderstandings about the ideas investigated by the question had increased significantly during the Macromolecules course. This increase in students' misunderstandings may be explained by the instruction strategy applied during the Macromolecules courses. The independent investigation settings applied in the Macromolecules course allows students to have the opportunity of gathering information from a variety of sources. The interview results also support that the majority of the students had used secondary or tertiary sources of information from the internet. The increase in students' misunderstandings may stem from those sources. Harrison and Treagust (2002) suggested that more research is needed to inform practice about how the development of ideas should be introduced at university level. The findings of this current study suggest that independent investigations, if applied in settings similar to the Macromolecules course, might lead to an increase in the number of misunderstandings.

6) Isomerisation Question

This question was intended to measure students' understanding of the cis- and trans- stereochemistry of polymers and the impact of these different stereoisomerisms on polymers behaviours in chemical reactions. Table 6.14 shows that there was a significant positive change in the students' responses, which implies that some students had learned something about geometric isomerisation during the Macromolecules course.

		Mean	**Mean Difference**	**Std. Deviation**	**95% Confidence Interval of the Difference**		**Sig. (2-tailed) p value**
	Pre- Isomerisation Question	6.95	.658	2.165	.173	1.143	.008
	Post- Isomerisation Question	7.61					

Table 6. 14: Results of the Paired Sample T-Test for the Isomerisation Question

Comparison of the pre- and post-intervention surveys shows that the p value is smaller than 0.05. This suggests that the Macromolecules course had a significant impact on students' learning of the geometric isomerisation idea.

As can be seen from Figure 6.6, there was an increase in the number of all-correct answers with no evidence of misunderstanding, and a decrease in responses coded D, which explains the significant change in responses at the post-intervention analysis compared with the pre intervention analysis.

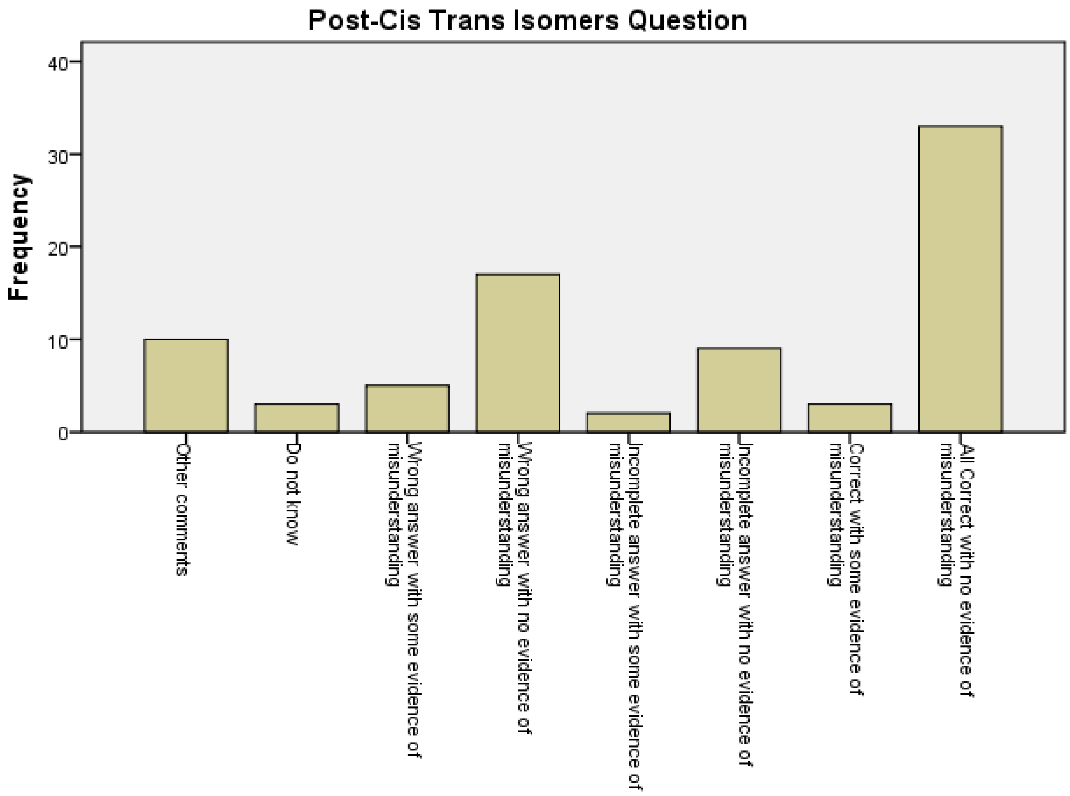


Figure 6. 6: The Frequencies of the Responses to the Isomerisation Question after the Intervention

In terms of students' misunderstandings, Table 6.15 shows the results of the change in the number of responses with a sign of misunderstanding.

	Pre-Intervention Isomers Question	Post-Intervention Isomers Question	
Number of 2-coded Responses	7	5	12
Number of 1-coded Responses	75	74	149
	82	79	161

Table 6. 15: Chi-Square Test for the Isomerisation Question

$\chi^2 = 0.36$

Since 0.36 < 3.84, the researcher accepts the null hypothesis and the difference is not statistically significant.

Discussion:

The most common wrong answer from respondents was related to the wrong interpretation of the steric effects in molecules. Even though many students were able to recognise that steric impact plays a role in polymers' elasticity and brittleness, they were not able to make the right connection. For instance,

> *Due to steric effects, the trans polymer will be elastic and the cis polymer will be brittle at room temperature.*

The student who gave this response clearly misunderstood geometric isomerism and thought that trans- isomers would have more steric hindrance.

> *Due to steric hindrance the trans conformation will have higher elasticity than the cis conformation. The cis conformation would be the most brittle as the molecules have less freedom to move.*

In this example, the student associated the movement of the molecules with the elasticity of the polymer. However, the elasticity of the polymer is related to the movement of the polymers as a whole rather than the molecules encompassed by the polymer.

In the post-intervention data analysis, the number of exemplified responses was again observed not to have diminished. Those findings fit in with the literature about students' ideas of isomerisation. Isomerisation, in general as an idea in chemistry, is seen as quite problematic by many students and there may be different reasons for this. First, there is still a discrepancy between the description of isomerism and its application in teaching and research. Also, iso-classification leads students to believe that compounds must be from the same class to be isomers. For example, an alcohol cannot be an isomer with ether or *vice versa* (Schmidt, 1992). The most common suggestion from the literature for overcoming problems in teaching and learning isomerism is the use of visualising tools. Barrows and Eberlein (2004) also suggested that the use of molecules which do not fit in the common rules about isomerism (for instance, showing an example of a molecule whose cis-isomers are more chemically inert than its trans-isomers) might be helpful for students to reach a deep understanding. Surprising results constitute a 'discrepant event', and making the effort to understand it offers students an opportunity to develop a deeper and more sophisticated comprehension of the underlying organic chemistry. On the other hand, the independent learning approach applied in the Macromolecules course does not seem to be effective at overcoming misunderstandings in this topic.

7) Kevlar's Strength Question

This question focused on students' knowledge acquisition of the intermolecular bonds in polymers. The topic of Kevlar's intermolecular forces was covered in the Macromolecules course's workbook. In the pre-test results, almost a third of the students were able to give an expected answer to this question and in the post-test data, this number had increased to 70%. Table 6.16 shows the significance of the change in the responses.

		Mean	Mean Difference	Std. Deviation	95% Confidence Interval of the Difference		Sig. (2-tailed) p value
	Pre- Kevlar's Str. Question	7.68	1.494	2.417	.952	2.035	.000
	Post- Kevlar's Str. Question	9.18					

Table 6. 16: Results of the Paired Sample T-Test for the Kevlar's Strength Question

Comparison of the pre- and post-intervention surveys shows that the p value is smaller than 0.05, which suggests that some students had learned something about intermolecular bonding in Kevlar.

Figure 6.7 shows that there were only three different types of response in the post-intervention data. Compared with the pre-intervention responses, the students' responses were more consistent after the Macromolecules course.

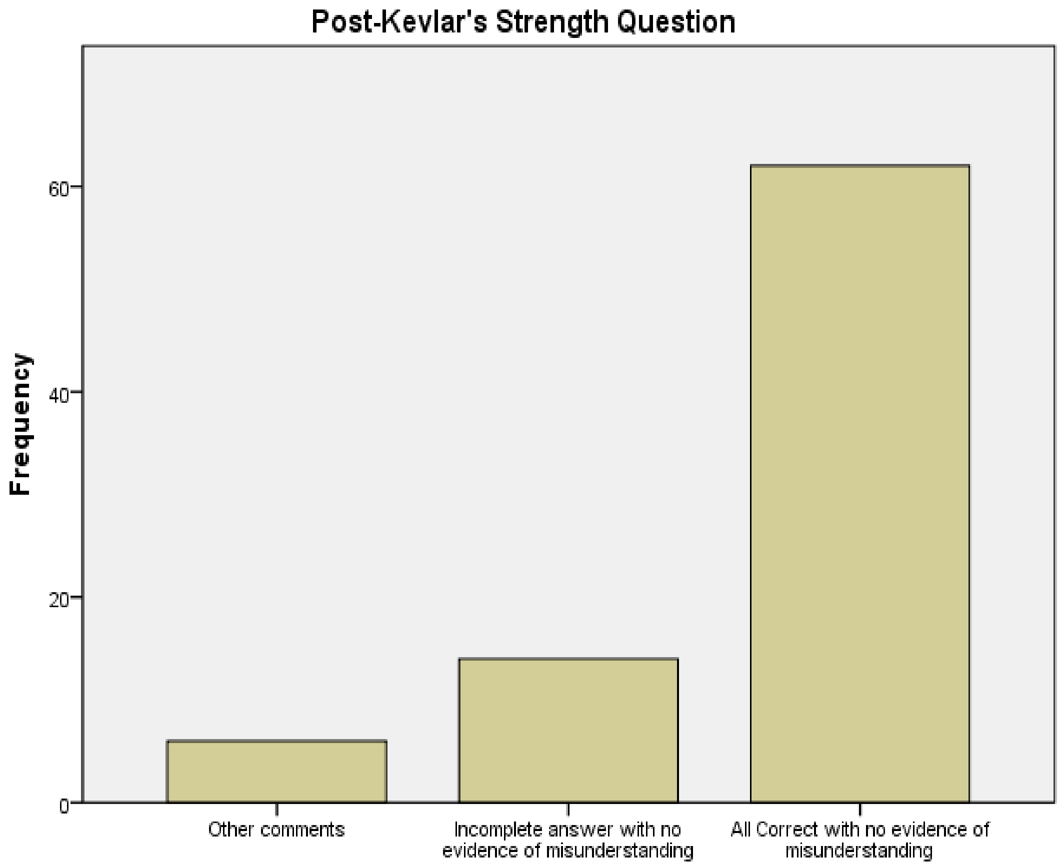


Figure 6. 7: The Frequencies of the Responses to the Kevlar's Strength Question after the Intervention

In terms of students' misunderstanding, at the post-intervention analysis, there was only one response that was considered to show a sign of misunderstanding. Table 6.17 shows the significance of the change in the number of responses that included a sign of misunderstanding.

	Pre-Intervention Kevlar's Strength Question	**Post-Intervention Kevlar's Strength Question**	
Number of 2-coded Responses	3	1	4
Number of 1-coded Responses	79	78	157
	82	79	161

Table 6. 17: Chi-Square Test for the Kevlar's Strength Question

$\chi^2 = 1.06$

Since 1.06 < 3.84, the researcher accepts the null hypothesis and the difference is statistically not significant.

Discussion:

The most significant mistake made by students in this question was that some students associated the physical strength of Kevlar with its atom-atom interaction in the molecules (intramolecular bonds) instead of atom-atom interactions among different molecules (intermolecular bonds). In other words, some students thought that if in the molecule there is a strong bond between atoms, the molecule should be physically strong. However, the strength of the intramolecular bonds makes a molecule chemically inert (which may be referred to as stronger). The physical strength of molecules stems from their intermolecular interactions. For instance,

> *The main reason for Kevlar's strength is that along the length of one polymer molecule there are many strong chemical bonds which are not easily broken, eg. C-N, C-C.*

This student associated Kevlar's physical strength with its chemical inertia. One molecule can be physically very strong but chemically quite active and could easily react with other chemicals. This finding matches the findings of other researchers who have claimed that students struggle to understand the relationship between intermolecular bonding and physical properties (Peterson & Treagust 1989; Peterson *et al*. 1989; Taber 1995, 1998). The students' misunderstanding about Kevlar's physical strength stemming from the intramolecular bonds may be associated with undergraduate university students' misunderstandings that *"physical change, such as boiling, breaks covalent bonds"* (Henderleiter, Smart, Anderson & Elian, 2001) as in both cases students associate physical change with intramolecular bonds. During the Macromolecules course, there was no statistically significant change observed in students' misunderstandings about the intermolecular forces.

8) Disposal of Kevlar Question

As discussed in the previous chapter, the responses given to this question in the pre-intervention data analysis were mainly coded D. The question was intended to observe any impact of the Macromolecules course on students' ability to generate creative solutions to chemistry-related problems. The question produced a variety of answers and there was no particular theme observed among the wrong answers. Table 6.18 shows the significance of the change in the responses. The main reason for this result is the decrease in the number of responses coded D and the increase in the number of responses coded A.

		Mean	Mean Difference	Std. Deviation	95% Confidence Interval of the Difference		Sig. (2-tailed) p value
	Pre- Dispose of Kevl. Question	6.76	1.190	2.670	.592	1.788	.000
	Post-Dispose of Kev. Question	7.95					

Table 6. 18: Results of the Paired Sample T-Test for the Disposal of Kevlar Question

Comparison of the pre- and post-intervention surveys shows that the p value is smaller than 0.05, which suggests that the students' creativity in generating solutions using their chemical knowledge had changed significantly during the Macromolecules course.

Figure 6.8 shows that even among the post-intervention responses there was quite a variety of differently coded responses. However, there was a significant shift towards responses considered as all-correct with no sign of misunderstanding.

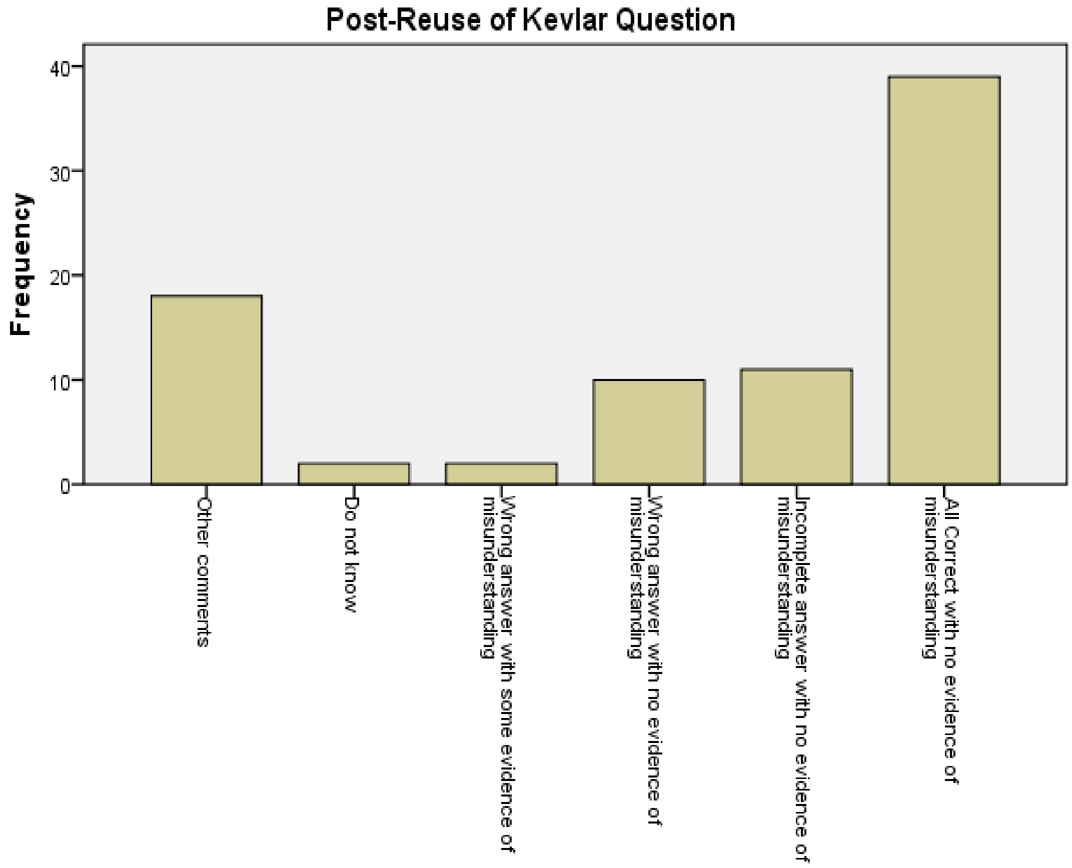


Figure 6. 8: The Frequency of the Responses to the Disposal of Kevlar Question after the Intervention

In terms of students' misunderstandings; there was no particular sign of misunderstanding detected among the students' responses, so there was no need for chi-square calculations.

Discussion:

As has been discussed in the literature, the merit of being a chemist is not just having knowledge about chemistry as a subject but more about shaping one's way of looking at and thinking about the world. In a broader sense, chemistry can be seen as a quest for revealing the identity of substances, understanding diversity in the material and biological world, explaining similarities and differences, transforming nature, and creating things which many might consider impossible (Hoffmann, 1995). So the way chemists think, build and use models, represent systems and processes, observe appropriately, design experiments, interpret findings and generate explanations and correlate findings with other problems and explanations are the types of knowledge and attributes that undergraduate chemistry students may find useful and can utilize in their future studies and work. All of these actions require some sense of creativity, and research studies on curriculum design support the idea that creativity and similar types of abilities are likely to be needed by students in their future (Mbajiorgu & Reid, 2006). Although it is hard to claim from the results of one question, the findings of this current research study suggest that independent learning approaches may have a positive impact on students' creative thinking.

6.4 Test 2

1) Functional Groups Question

This question was intended to measure students' knowledge acquisition about functional groups, which are commonly encompassed by polymers in medical chemistry. This piece of knowledge was expected to be covered by students during their independent investigations. The majority of the responses gave the expected answer. Almost every student was successful at detecting functional groups in polymers. However, they were not as successful at naming them. There was no detected sign of misunderstandings while they were trying to identify functional groups. The results of the paired sample t-test are shown in Table 6.19.

		Mean	Mean Difference	Std. Deviation	95% Confidence Interval of the Difference		Sig. (2-tailed) p value
	Pre- Func. Groups Question	8.58	-0.97	1.277	-.421	.227	.553
	Post-Func. Groups Question	8.48					

Table 6. 19: Results of the Paired Sample T-Test for the Functional Groups Question

Comparison of the pre- and post-intervention surveys shows that the p value is bigger than 0.05, which suggests that the students' knowledge acquisition during their personal investigations about the functional groups commonly used in medical chemistry had not increased significantly.

In the response frequencies, there was a slight shift from expected answers to incomplete answers with no sign of misunderstanding. That shift explains the negative mean change (-0.97) and may be interpreted as students' knowledge lessening during the Macromolecules course. Figure 6.9 shows the frequencies of the responses given in the post-intervention data collection. As can be seen, there were only three codes used to analyse the data.

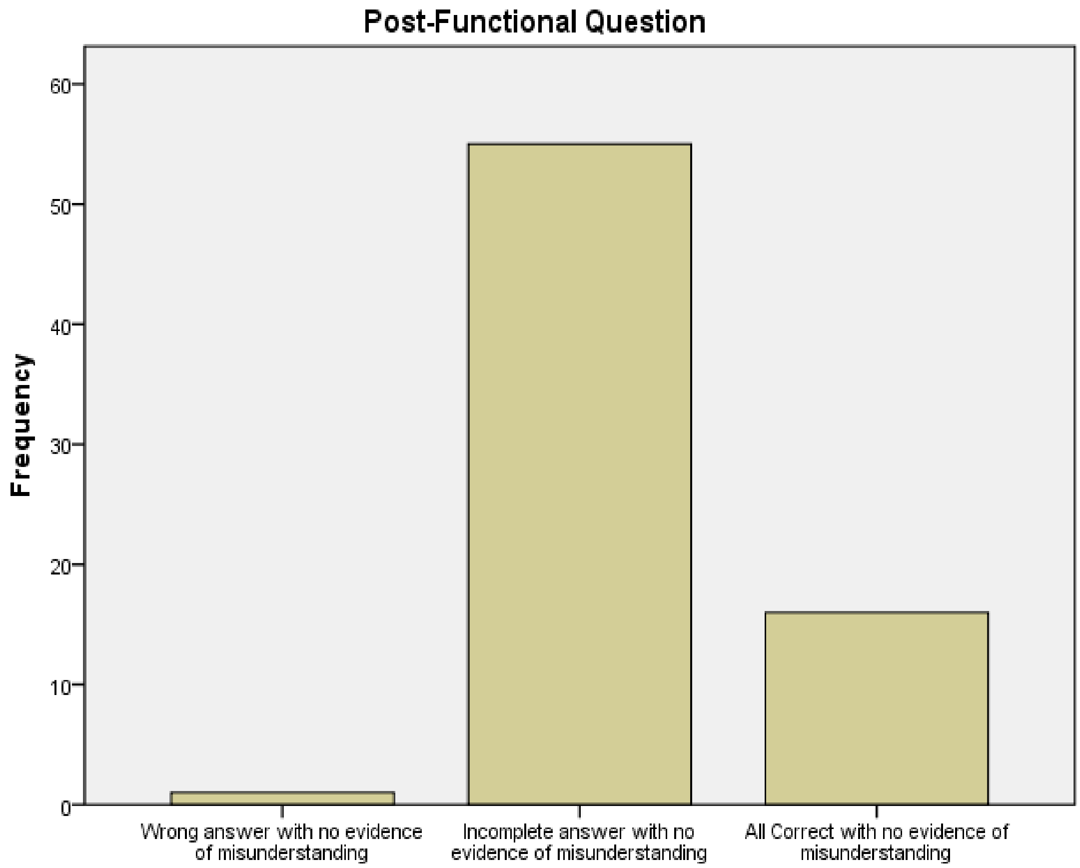


Figure 6. 9: The Frequencies of the Responses to the Functional Groups Question after the Intervention

There was no response with a sign of misunderstanding in the post-intervention analysis or the pre-intervention analysis.

Discussion:

The most common problem in the responses to this question was that the students struggled to name the functional groups. In the pre-test responses, there were some students who thought that a functional group was only the element that was bonded to the polymer (such as phosphorus) instead of the phosphonic acid group, or carbon instead of carboxylic acid. In the post-test, they gave similar responses, particularly for the phosphonic acid group, such as '*phosphorus compound*'.

Moreover, in the pre-test and post-test responses, there were some students who confused oxoacids with alcohols due to the fact that oxoacids have a hydroxyl group or groups. In the post-test, the number of students who had the same confusion had decreased, but this decrease was not statistically significant. Some students were still not competent in their ability to separate oxoacids from alcohols.

One interesting change in the post-test was that the students' were better at identifying ester linkage in caprolactone. In the pre-test results, they were again able to recognise the ester group but they defined it as if it were two different groups (ketone and ether). This implies that they had learned ester linkage as a functional group name; however this did not have any positive impact on the results as responses in which ester linkage was defined as two different groups (which was often the case in the pre-intervention responses) were also considered as fully-correct answers.

2) Biodegradability and Biocompatibility Question

This question investigated students' understanding of those two ideas, which are particularly popular for polymers used *in vivo*. The significance of the change in the responses before and after the Macromolecules course is presented in Table 6.20.

		Mean	Mean Difference	Std. Deviation	95% Confidence Interval of the Difference		Sig. (2-tailed) p value
	Pre- Biodeg.& Bioc. Question	6.95	.448	2.078	.021	1.076	.052
	Post- Biodeg.& Bioc.Question	7.50					

Table 6. 20: Results of the Paired Sample T-Test for the Biodegradability and Biocompatibility Question

Comparison of the pre- and post-intervention surveys shows that the p value is bigger than 0.05, which suggests that the students' knowledge and understanding of the ideas of biodegradability and biocompatibility had not changed significantly during the Macromolecules course.

In the post-intervention analysis of the item, there was a decrease in the responses coded D and an increase in responses coded B. However, the number of responses coded B was still quite high compared with A-coded answers. The frequencies of the responses are shown in Figure 6.10.

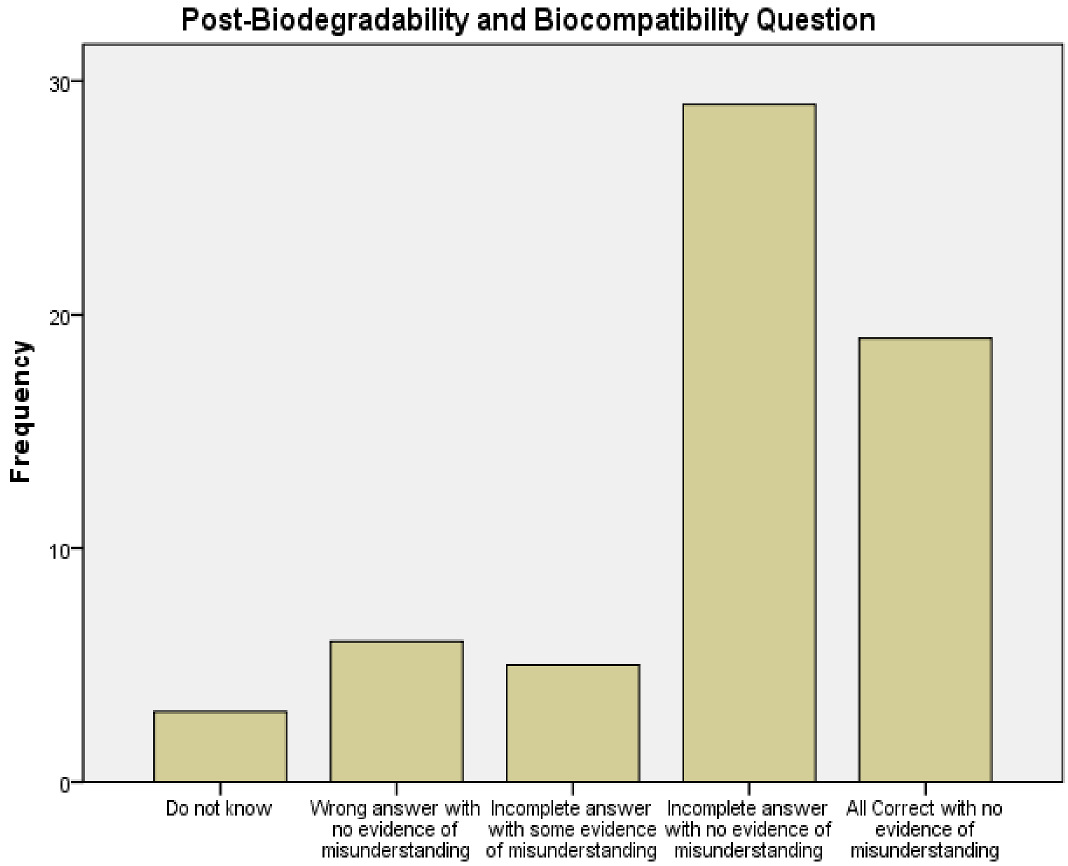


Figure 6. 10: The Frequencies of the Responses to the Biodegradability and Biocompatibility Question after the Intervention

In terms of students' misunderstandings, there was no significant change in the post-test results, as shown in Table 6.21.

	Pre-Intervention Biodegradability and Biocompatibility Question	**Post-Intervention Biodegradability and Biocompatibility Question**	
Number of 2-coded Responses	3	5	8
Number of 1-coded Responses	59	54	113
	62	59	121

Table 6. 21: Chi-Square Test for the Biodegradability and Biocompatibility Question

$\chi^2 = 0.86$

Since 0.86 < 3.84, the researcher accepts the null hypothesis and the difference is not significant.

Discussion:

In the pre-test investigation, two themes of misunderstanding were identified. First, biocompatibility was understood by two students as polymers' ability to bond to the human body. Second, biodegradability was confused with the dissolution of polar polymers in polar solvents. There was no change in either of these misunderstandings in the post-intervention results and the same two answers were observed in the post-test responses.

It is important to emphasize that the number of incomplete answers was still larger than the number of expected answers in the second test. That result stems from the fact that in the post-test analysis, almost half of the students had some kind of inadequate explanation for defining the features of polymers that make them biodegradable and biocompatible. Almost a third of the students had investigated only one of the ideas for both of the polymers, although the question had asked them to investigate both of the ideas for both of the polymers. All of those answers were coded B1.

Table 6.21 shows that the number of responses with a sign of misunderstanding about the ideas of biodegradability and biocompatibility slightly increased but had not changed significantly during the Macromolecules course.

3) Chelate Forming Question

This question measured students' understanding of coordinate bonds. In the pre-intervention results, the chelate forming question had one of the lowest numbers of correct response in the test. This result had not changed much in the post-intervention responses and the question again generated the lowest number of correct answers. The significance of the difference between the two tests is shown in Table 6.22.

		Mean	Mean Difference	Std. Deviation	95% Confidence Interval of the Difference		Sig. (2-tailed) p value
	Pre- Chelate Form. Question	6.55	.290	2.198	-.268	.849	.302
	Post- Chelate Form. Question	6.84					

Table 6. 22: Results of the Paired Sample T-Test for the Chelate Forming Question

Comparison of the pre- and post-intervention surveys shows that the p value is bigger than 0.05, which shows that improvement in students' understanding of coordinate bonding was not statistically significant.

In the post-intervention frequency of responses shown in Figure 6.11, there was a slight shift from D-coded answers to C- and B-coded answers. On the other hand, A-coded answers were not affected much during the Macromolecules course.

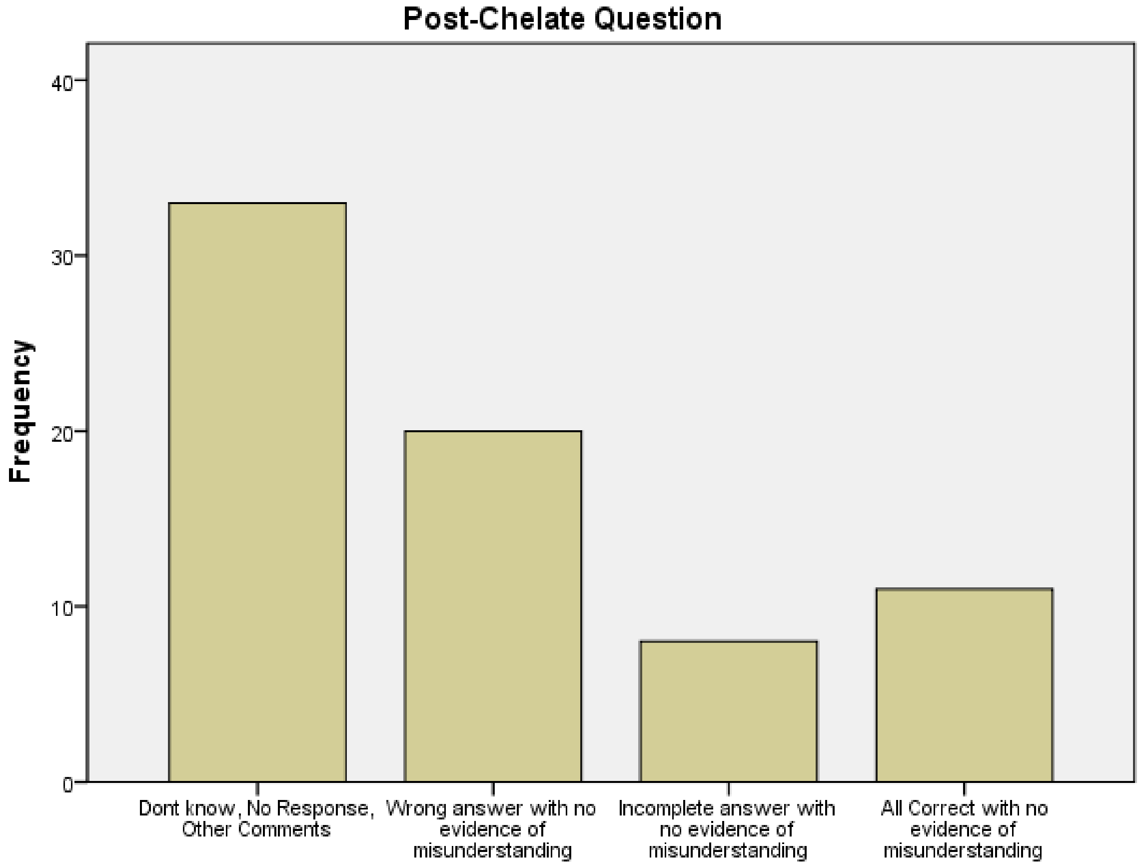


Figure 6. 11: The Frequency of the Responses to the Chelate Forming Question after the Intervention

There was no sign of misunderstanding observed in either the pre- or the post-intervention data analysis.

Discussion:

The results imply that the students' understanding of coordinate bonding and chelate formation in the structure of polymers had not been affected significantly during the Macromolecules course.

The question did not generate any response with a sign of misunderstanding. One possible reason for this result is the high number of D-coded answers in both tests. As discussed earlier, the question required a drawing from students and their ability to draw the correct structure was quite low. The results might have differed if a verbal explanation had been asked from students.

The most significant challenge for the students in both tests, before and after the Macromolecules course, seemed to be to define and draw the coordinate bonding. In a coordinate bond, both electrons come from the same atom. In the question, for chelate formation, oxygen atoms' free electron pairs are used to create a coordinate covalent bond with Ca^{+2} ions. The students were able to recall this piece of information but they seemed not to comprehend that the formation of the octet is generally taken as the criterion for forming a bond. So, only single-bonded oxygen atoms can create coordinate covalent bonds as they have not reached the octet yet. Double-bonded oxygen atoms, as they have already reached the octet, cannot form coordinate covalent bonds. However, the majority of the students thought that double-bonded oxygen atoms can create coordinate covalent bonds as well. An example of a student's answer is shown as Figure 6.12.

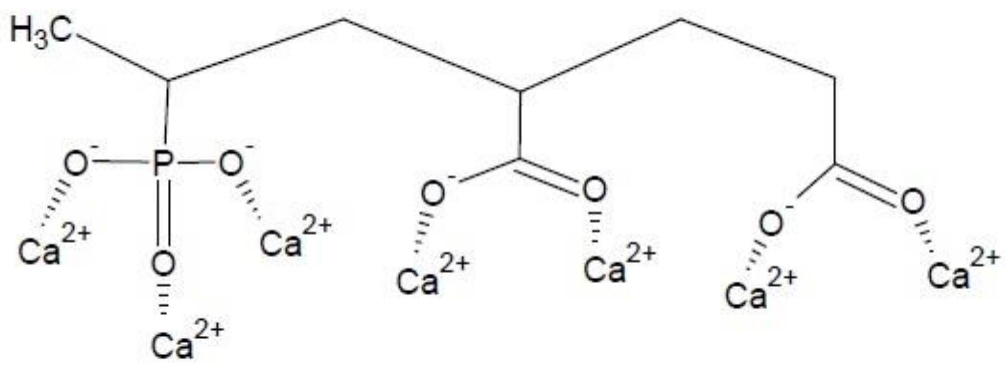


Figure 6. 12: Example of a Student's Answer

There are two main problems with this type of answer. First, as mentioned above, students who gave this answer thought that every oxygen atom can have coordinate bonds. Second, they thought that calcium ions have only one coordinate bond although they actually have two positive charges. Their mistake might stem from the notion that Ca^{+2} atoms have two of the electrons from oxygen atoms. In fact, however, coordinate bonding is a covalent bonding type and two electrons that come from same atom (oxygen atoms in this case) are shared between calcium and oxygen atoms. Hence, Ca^{+2} can accommodate two coordinate covalent bonds. Deep investigation of students' understanding of this issue requires further research.

Another important issue to be discussed about this question was that the students made several chemical and logical mistakes in their drawings. There were many oxygen atoms that made more than two bonds, carbon atoms with more than four bonds, open ended bonds and so on. In the post-investigation responses, the number of those examples had decreased slightly, however there were still many and the decrease was not statistically significant.

4) Wettability of Polymers Question

This question was similar to the combustion question in Test 1. It probed students' scientific reasoning through an idea which students experience very often in their everyday life; wetting. It was expected that students learn much about wetting from their experiences in life. The conclusions drawn from those experiences might differ from the information which chemistry teaches to students. Moreover, conclusions drawn from students' everyday life experiences may also be obstacles that impede the understanding of the ideas which are taught in chemistry courses. This question was intended to monitor the impact of the independent learning approach on students' ways of interpreting this natural phenomenon.

The significance of the difference in the answers given to this question was calculated using a paired sample t-test and the results are shown in Table 6.23.

		Mean	Mean Difference	Std. Deviation	95% Confidence Interval of the Difference		Sig. (2-tailed) p value
	Pre- Wettability Question	7.13	.758	2.821	0.42	1.474	.038
	Post- Wettability Question	7.89					

Table 6. 23: Results of the Paired Sample T-Test for the Wettability Question

Comparison of the pre- and post-intervention surveys showed that the p value is smaller than 0.05, which suggests that some students' ways of thinking about the wetting idea had shifted from naïve everyday life explanations to more scientific ones.

As can be seen in the frequency bar chart shown as Figure 6.13, the most significant shift in answers was from C- and D-coded answers to A-coded answers. The number of students who gave a correct answer with no sign of misunderstanding had increased significantly.

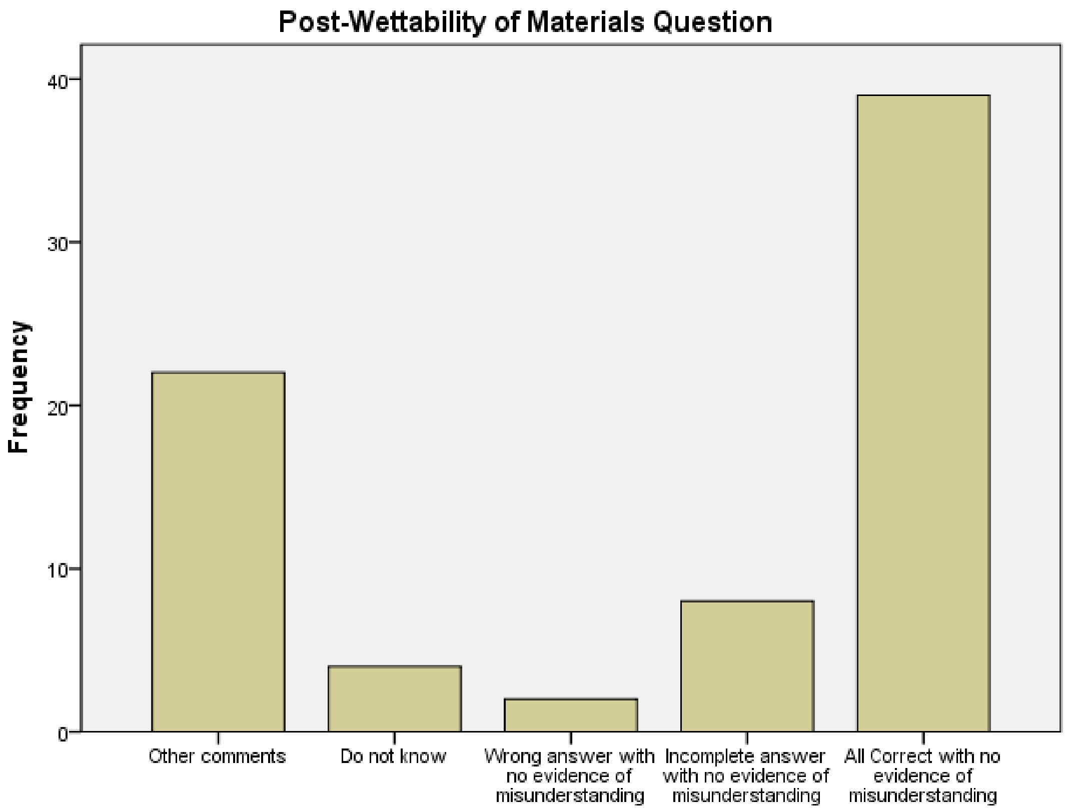


Figure 6. 13: The Frequencies of the Responses to the Wettability Question after the Intervention

As reported in the previous chapter, there was no response coded 2. This signifies that the researcher found no answers with any sign of misunderstanding in the pre-intervention responses. The same result was found in the post-intervention results.

Because there was no answer coded 2 in either the pre- or the post-intervention surveys, there was no need to examine the difference in misunderstanding the ideas in this question.

Discussion:

These results show that the students' explanations of the wetting phenomenon had shifted from everyday life explanations towards more scientific ones. In some examples of their responses, this shift is illustrated clearly: for example

> *Angles decrease when PVPA mixed to PCL and this increases wettability. PVPA has –COOH and –OH functional groups which make the groups polar. PVPA/PCL has many of those polar groups which increase its polarity and wettability. There are also more hydrogen bonds to increase wettability.*

On the other hand, in the pre-test results, their explanations often reflected their everyday life experiences: for example

> *The contact angle is smaller meaning it can trap the water in and means it is more probable that it will react.*

As can be seen from the second response, the student attributed the change in the behaviour of the polymers to his/her own everyday life experiences. S/he used the word 'trap' to describe the polymer molecules' chemical behaviour. However, in the post-test answer, s/he emphasized the polarity and the reasons for this polarity of the polymer. Those variables differ in chemical explanations from students' everyday life experiences. It might be claimed that the explanations had moved closer to scientific explanations after the Macromolecules course.

This question was one of the questions which did not generate any response with a sign of misunderstanding.

5) Mechanical Strength of PVPA/PCL Question

The mechanical strength of PVPA/PCL question investigated the change in the students' understanding of the hydrogen bonds in polymers. Table 6.24 shows the significance of the change in the responses before and after the Macromolecules course.

		Mean	Mean Difference	Std. Deviation	95% Confidence Interval of the Difference		Sig. (2-tailed) p value
	Pre- Mec. Strength Question	7.16	1.226	2.272	.649	1.803	.000
	Post- Mec. Strength Question	8.39					

Table 6. 24: Results of the Paired Sample T-Test for the Mechanical Strength Question

Comparison of the pre- and post-intervention surveys showed that the p value is smaller than 0.05, which suggests that some students had learned something about hydrogen bonds in polymers during the Macromolecules course.

In terms of frequency changes, the responses showed similar figures to the previous question. The most significant shift was from D- and C-coded answers to A-coded answers. The frequencies are shown in Figure 6.14.

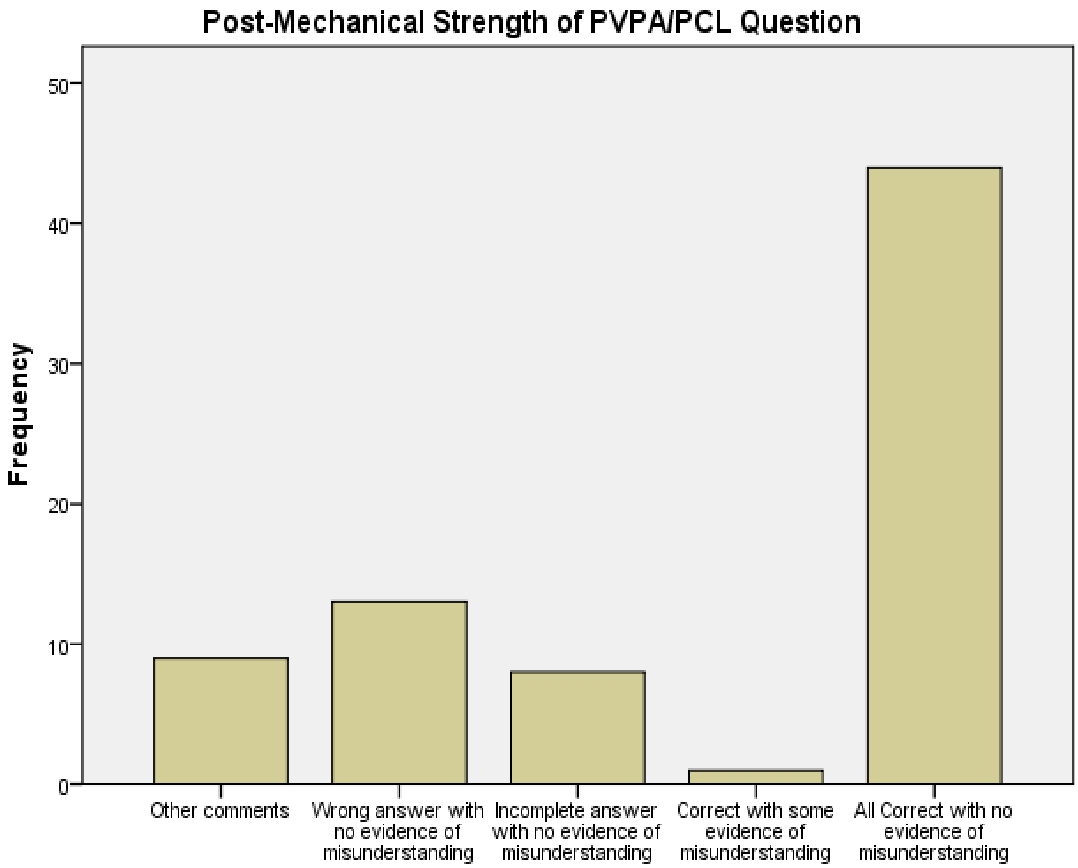


Figure 6. 14: The Frequency of the Responses to the Mechanical Strength after the Intervention

In terms of the students' misunderstandings, the question generated only one response with a sign of misunderstanding in the pre-intervention data. In the post-intervention phase, there was again only one response coded with a sign of misunderstanding and the response was almost the same as the response coded 2 in the previous test.

> *PCL/PVPA scaffold is stronger than PCL scaffold as it has more hydrogen bonds. PVPA is more branched and it is surface is low. Hence a PCL/PVPA polymer is less regular and more branched making the compressive strength higher.*

It was the same student who gave the same answer to the same question in the later test. The significant point here is that the misunderstanding that the student had (more branching means less surface) was not related to the idea being investigated and the response was coded A2. As there was no change in the number of answers coded 2 in both tests, the chi-square test was not applied.

Discussion:

The results show that hydrogen bonding in polymer chemistry can be seen as a less problematic idea compared with the other ideas investigated in this research study. The one misunderstanding detected in both tests was not relevant to the idea being investigated. In terms of the impact of the Macromolecules course, it can be claimed that the course had helped the students to learn more about hydrogen bonding significantly. In terms of students' misunderstandings, there was no significant change between the pre- and post-intervention data.

6) Calculation Question

The question was intended to investigate students' self-assessment ability before and after the instruction strategy being investigated. The significance of the change in the responses is shown as Table 6.25.

		Mean	Mean Difference	Std. Deviation	95% Confidence Interval of the Difference		Sig. (2-tailed) p value
	Pre- Life Guarantee Question	7.52	-.355	2.128	-.895	.186	.194
	Post- Life Guarantee Question	7.16					

Table 6. 25: Results of the Paired Sample T-Test for the Calculation Question

Comparison of the pre- and post-intervention surveys showed that the p value is bigger than 0.05, which suggests that there was no statistically significant change in the students' ability to use a self-assessment strategy during the Macromolecules course.

As discussed in the previous chapter, the number of D-coded answers was quite low for this question and this number had decreased even more in the post-intervention analysis. There was a slight shift from A-coded answers towards answers coded B and C and this shift can be seen in Figure 6.15.

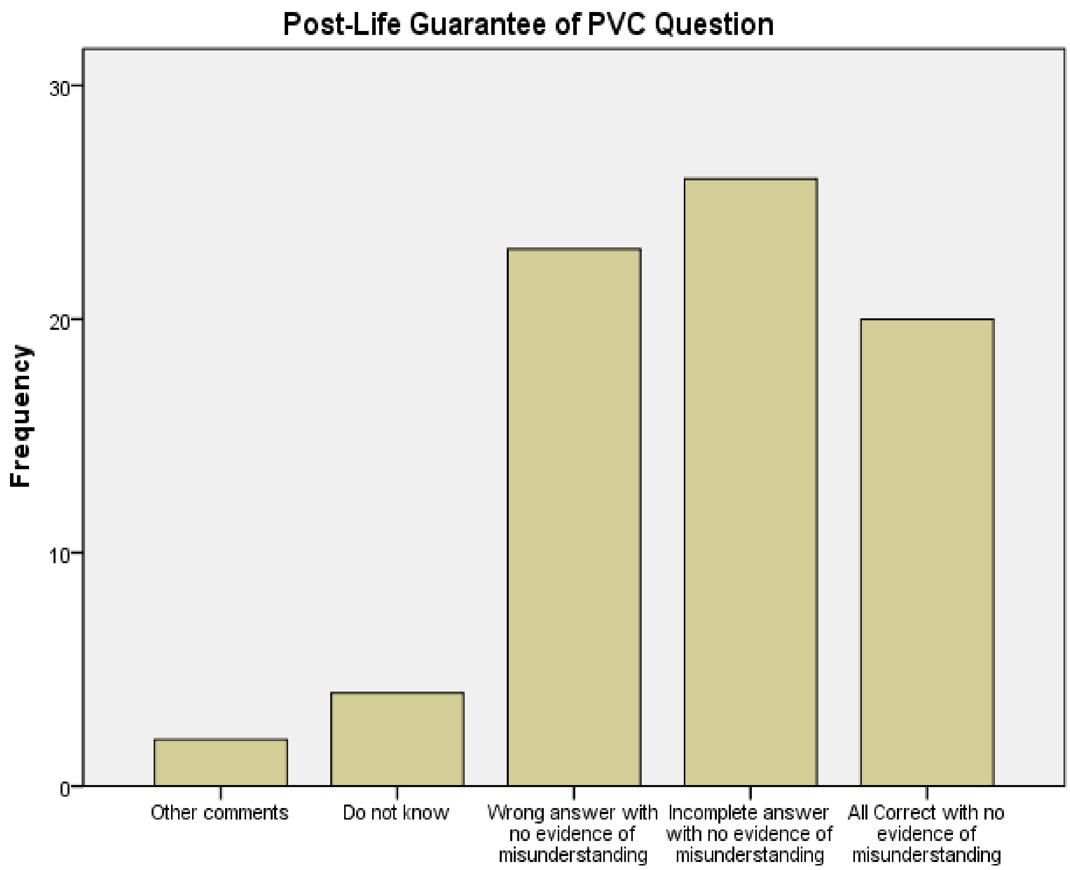


Figure 6. 15: The Frequencies of the Responses to the Life Guarantee of PVC Question after the Intervention

There was no investigation of students' misunderstandings over this question.

Discussion:

It was recognised in the pre-intervention results reported in the previous chapter that the most significant problem for the students was the unit conversion necessary for this question. The majority of the students were able to put the equations together to reach a solution, but because they failed to make the required unit conversions, they failed to arrive at correct the answer and produced an unfeasible answer instead. In the post-intervention responses, there was no change observed on this issue. For instance, the number of students who had given the clearly impossible 10^{-20} years as an answer for a suggested warranty period was almost the same among the post-intervention responses.

Although considering that the data was generated from only one question, it is hard to be used as an evidence, it shows that there was no significant impact on students' self-assessment ability to recheck their answers if the results are not sensible. The results suggest that the students' self-assessment ability (which is considered to be a metacognitive component in independent learning) had not changed significantly during the Macromolecules course.

7) Polarity Question

This was one of the questions in the test that investigated students' understanding of the polarity of molecules, and the impact of the polarity of molecules on the chemical and physical features of polymers. The students were expected to develop an understanding of this idea during their personal investigations. The significance of the change between the two tests is shown as Table 6.26.

		Mean	Mean Difference	Std. Deviation	95% Confidence Interval of the Difference		Sig. (2-tailed) p value
	Pre- Polarity Question	7.97	.694	2.826	-.024	1.411	.058
	Post- Polarity Question	8.66					

Table 6. 26: Results of the Paired Sample T-Test for the Polarity Question

Comparison of the pre- and post-intervention surveys showed that the p value is bigger than 0.05, which suggests that the change in students' understanding of the investigated idea had not changed significantly during the Macromolecules course.

Compared with other items in the test, this question generated relatively more correct answers during the pre-intervention survey. The post-intervention data showed similar themes: the frequency of A-coded responses had slightly increased and the frequencies of D- and C-coded responses had slightly decreased after the intervention. However, these changes were not big enough to create a statistically significant difference. The later frequencies are shown in Figure 6.16.

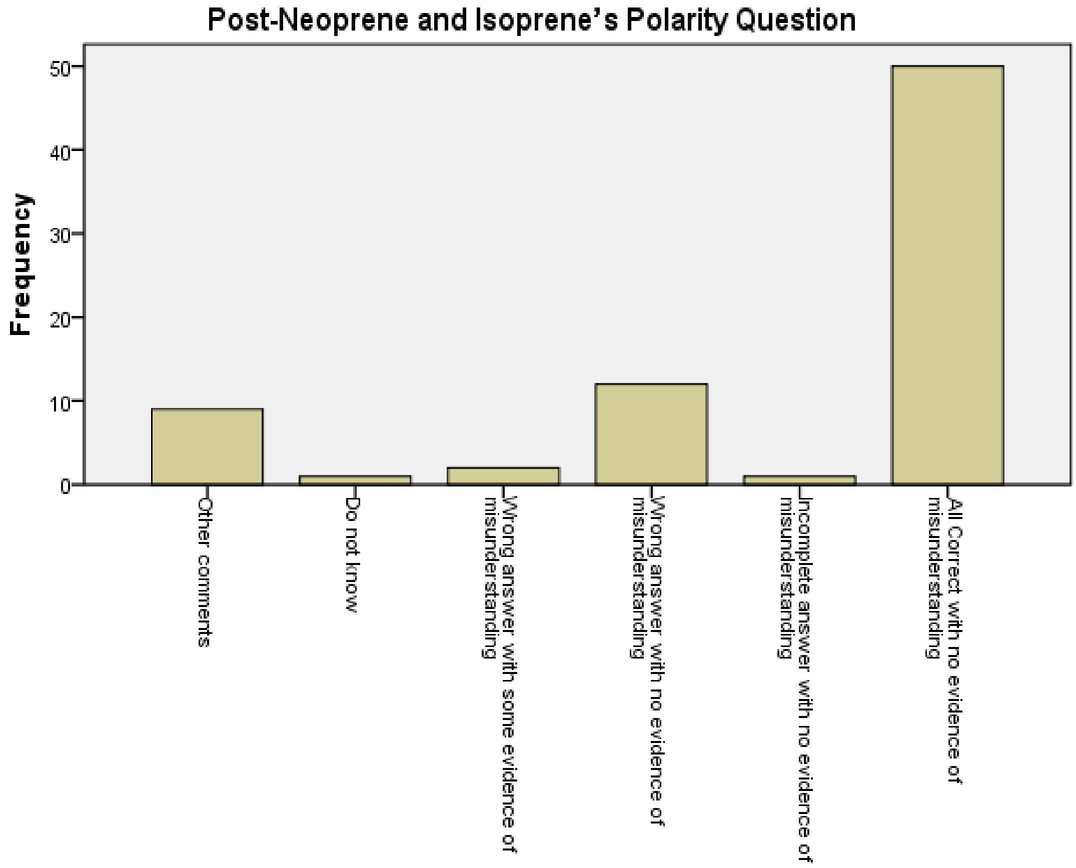


Figure 6. 16: The Frequencies of the Responses to the Polarity Question after the Intervention

In terms of the students' misunderstandings, there were four 2-coded responses in the pre-intervention data and three 2-coded responses in the post-intervention data. The significance of this change was calculated using a chi-square test and the results are shown in Table 6.27.

	Pre-Intervention Polarity Question	Post-Intervention Polarity Question	
Number of 2-coded Responses	4	3	7
Number of 1-coded Responses	48	49	97
	62	52	104

Table 6. 27: Chi-Square Test for the Polarity Question

$\chi^2 = 0.24$

Since 0.24 < 3.84, the researcher accepts the null hypothesis and the difference is not significant.

Discussion:

This question was answered correctly with no sign of misunderstanding by around 50% of the students in pre-intervention results and this number had increased to around 53% in the post-intervention results. These numbers reflect an increase in students' understanding of polarity, although this increase is statistically not significant.

In terms of the students' misunderstandings, the most common problem was that four students had thought that polyisoprene is a polar polymer as it has more than one type of atom. Some students were not able to recognise that, on the Pauling scale, the electronegativity values of C and H atoms are so close that their difference can be ignored. Hence, molecules (therefore polymers) that are composed of only C and H atoms are considered as non-polar. After the Macromolecules course, the students' understanding of those ideas seemed to have improved. For instance,

> *Isoprene for brake pipe and neoprene for fuel pipe. Polar should go into non-polar; non-polar should go into polar. Otherwise they would solve each other ...*

One improvement observed in the students' responses was related to their wording. The number of students who could use the solubility word correctly had increased in the post-intervention responses; they used the term 'solubility' more often and more competently. In the pre-intervention examples, however, the majority of students had used the word 'interaction' in order to describe solubility.

Table 6.27 shows that students' misunderstandings about the idea of polarity had not been affected significantly during the Macromolecules course.

8) Contact Lenses' Structure Question

As mentioned in the previous chapter, this question was intended to measure the students' ability to transfer their knowledge to different contexts. They were given two polymers which were quite unfamiliar to their A-level knowledge and were asked to explain their structure-property relationship: the only difference in the two polymers' structures was their functional groups. The number of expected correct answers to this question was quite low considering the results generated in the pre-intervention data analysis. However, it was hoped to see an improvement in their understanding of the structures of more complex polymers. The difference in their answers to the item between the two tests is shown as Table 6.28.

		Mean	Mean Difference	Std. Deviation	95% Confidence Interval of the Difference		Sig. (2-tailed) p value
	Pre- Contact Lenses Question	6.74	.484	2.102	-.050	1.018	.075
	Post- Contact Lenses Question	7.23					

Table 6. 28: Results of the Paired Sample T-Test for the Contact Lenses Question

Comparison of the pre- and post-intervention surveys showed that the p value is bigger than 0.05, which suggests that the students' ability to transfer their knowledge to novel contexts had not been affected significantly during the Macromolecules course.

In terms of the frequencies of the responses, there was a slight decrease in answers coded D. That suggests that the students felt more competent about giving an answer to this question in the post-intervention investigation. However, the increase was distributed between A-, B- and C-coded answers. This might be interpreted as showing that even though the students felt more competent in their post-intervention responses, their learning had not been improved significantly. Figure 6.17 shows the frequencies of the responses in the post-intervention data.

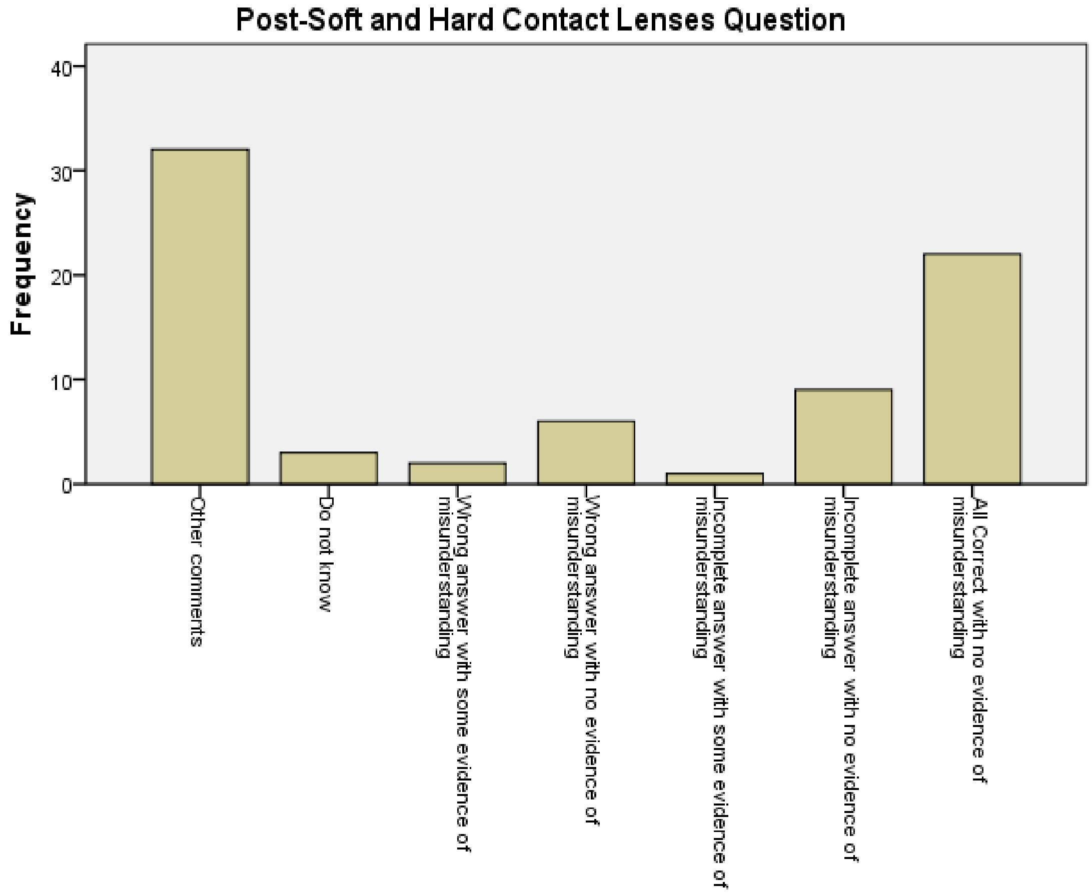


Figure 6. 17: The Frequencies of the Responses to the Contact Lenses Question after the Intervention

In terms of the students' misunderstandings, there was no change in the number of answers coded 2: there were three responses coded 2 in both phases. So the chi-square test was not employed.

Discussion:

In this case, the results once again suggest that the Macromolecules course had little or no impact on students' ability to transfer their knowledge to novel contexts. One possible reason for this result might be the fact that the question generated only 40 responses from the students. The majority of them were unable to give an answer to the question even after the intervention. It seems that this question was considered to be very hard by the students. This supports the students' comments on the difficulty level of this question. There was an increase in the number of students' who were able to divide big structured polymers with high molecular weights into manageable pieces and this increased the number of students who could give a correct answer to the question. Students who were able to recognise the common parts of two polymers (the methacrylate parts) also managed to recognise that the differences in the chemical or physical features of the two polymers were due to different functional groups. This change can suggest an improvement in their understanding since the process of managing polymers with high molecular weights into small pieces requires a cognitive process. The number of students who could apply this strategy had increased in the post-intervention responses. However, they were still not able to give the correct answer after they had managed to break down chunky polymer structures into small pieces.

6.5 Summary of the Findings

In this section, a summary of the findings will be presented and their implications will be discussed in detail. Before the start of this discussion, however, in order to see the results overall and to make drawing conclusions easier, Table 6.29 presents the results of all the questions.

The Name of the Question	Result of the Paired Sample t-Test	Result of the Chi-Square Test
Recycling Question	No Significant Difference	No Significant Difference
Branching Question	No Significant Difference	No Significant Difference
Combustion Question	**Significant Positive Difference**	No Significant Difference
PIC Question	No Significant Difference	Did Not Generate Data
Fashion Question	No Significant Difference	**Significantly Larger Number of Misunderstandings**
Isomerisation Question	**Significant Positive Difference**	No Significant Difference
Kevlar's Strength Question	**Significant Positive Difference**	No Significant Difference
Disposal Question	**Significant Positive Difference**	Did Not Generate Data
Functional Groups Question	No Significant Difference	Did Not Generate Data
Biodegradability Question	No Significant Difference	No Significant Difference
Chelate Question	No Significant Difference	Did Not Generate Data
Wettability Question	**Significant Positive Difference**	Did Not Generate Data
Mechanical Question	**Significant Positive Difference**	No Significant Difference
Calculation Question	No Significant Difference	Did Not Generate Data
Polarity Question	No Significant Difference	No Significant Difference
Contact Lenses Question	No Significant Difference	No Significant Difference

Table 6. 29: Overall Results

6.5.1 The impact of the Macromolecules course on students' knowledge acquisition

The *Recycling, Kevlar's Strength, PIC* and *Functional Group* questions were created to measure any impact on the students' knowledge about the Macromolecules course's content. The results of those questions showed that there was only a statistically significant increase in the students' knowledge on the topics which were covered in the first part of the course. In the first part, students were given a workbook which was prepared by the lecturer. The workbook was based on the lecturer's previous lecture notes which had been adapted to fit in with the principles of independent learning. These principles were explained in detail in section 3.2.3. The students were asked to start by working through this workbook, reading the sections, finding further information via weblinks and so on, and then attempt to answer the problems which were expected to guide students' learning of the topic. If they had problems with the work, they had access to a discussion board forum on the VLE in order to ask any questions.

On the other hand, there was no statistically significant change in students' knowledge about the topics which were covered in the second part of the course. For the second part of the course, students were asked to carry out an independent investigation into an aspect of polymer chemistry, and then present their findings in the format of a written article or short video. The polymer chemistry topics were assigned by the lecturer in the introductory lecture and students were allowed to pick whichever topic they wanted to study. Students were expected to pursue knowledge by asking questions that had piqued their natural curiosity. Detailed information about the course was presented in section 3.2.2.

6.5.2 The impact of the Macromolecules course on students' understanding of the ideas

The *Isomerisation* and *Mechanical Strength* questions were devised to measure any impact of the Macromolecules course on students' understanding of the ideas of geometric isomerisation and hydrogen bonding in polymer chemistry. These two ideas were covered in the first part of the course. The intention of preparing these two questions was to observe any impact of the independent learning approach applied in the first part of the course on students' understanding of the ideas. The results show that there was a significant improvement in their understanding of the two ideas after they had completed the course. This result suggests that students' understanding might be improved by independent learning approaches. On the other hand, in none of these questions was there a significant change in the number of responses with a sign of misunderstanding. This result may be interpreted as the independent learning approach is not an effective way of treating students' existing misunderstandings.

The *Branching, Biodegradability, Chelate, Polarity, Contact Lenses* and *Fashion* questions were intended to measure any impact of the Macromolecules course on students' understanding of the ideas covered in the second part of the Macromolecules course. These four questions investigated ideas which the students were expected to learn through their independent investigations from the second part of the Macromolecules course. The results show that there was no significant difference in their understanding of these ideas after the Macromolecules course. There was also no statistically significant difference in the number of responses with a sign of misunderstandings before and after they had completed the Macromolecules course. These results imply that the independent learning approach applied in the second part of the Macromolecules course is not an effective way of improving students' understanding of chemical ideas. Neither does it have any positive impact on improving students' misunderstandings.

Another significant result of the *Fashion* question was that after the Macromolecules course, there was a significant increase in the number of responses with a sign of misunderstanding. This can be interpreted as that the independent learning approach, if it is applied as it was in the second part of the Macromolecules course, may lead to an increase in students' misunderstandings. One possible reason for this result is students' choice of knowledge sources. Students prefer (or find it easier) to use secondary or tertiary information sources which in turn leads to them acquiring an increased number of misunderstandings. Control over students' knowledge sources seems to be a necessary provision in independent learning approaches.

6.5.3 The impact of the independent learning approach on students' ability of scientific reasoning

The *Combustion* and *Wettability* questions were prepared to measure any impact of the Macromolecules course on students' scientific reasoning. Those two questions investigated the students' approach to two everyday-life phenomena; combustion and wetting. The explanations which the students gave reflected their reasoning and any change in their way of thinking was examined. The results showed that there was a significant change in their responses before and after the Macromolecules course to those two questions. These changes represent a shift in students' explanations from non-scientific, naïve ideas to scientific explanations. These scientific explanations may be considered as representing an improvement in the students' scientific reasoning since these questions required students to transfer data generated through the sorts of interactions with or observations from the real world to a model's world. This ability of transfer is one of the four components of scientific reasoning described by Giere (1979). Hence, the results of these questions can be interpreted as showing that the independent learning approaches may be an effective way of improving students' scientific reasoning.

6.5.4 The impact of the independent learning approach on students' self-assessment ability

The *Calculation* question was created to measure the impact of the Macromolecules course on students' self-assessment ability. One of the common claims made for discovery instruction strategies is that they have a positive impact on students' self-assessment. However, the results generated in this current research study did not show any significant impact of the discovery instruction method on students' self-assessment ability. This result may be interpreted as showing that the independent learning approach applied in the Macromolecules course does not have a significant impact on students' ability of self-assessment in their learning.

6.5.5 The impact of the independent learning approach on students' ability to generate creative solutions to chemistry-related problems

The *Disposal of Kevlar* question was designed to measure any improvement in the students' creativity in generating solutions to chemistry-related problems. Especially considering the expectations of modern chemists to be more creative in generating solutions, one of the objectives of the Macromolecules course was to contribute to the preparation of a modern chemist. The results of this research study show that there was a significant increase in the students' ability to generate creative solutions to chemistry-related problems after the Macromolecules course. This result may be interpreted as showing that independent learning strategies may be effective ways of instruction in order to increase students' creativity in generating solutions to chemistry-related ideas.

6.6 Overall Effects

The responses to prepared diagnostic questions in this study provide evidence that the independent learning strategy applied in the first part of the Macromolecules course led to a statistically significant increase in students' knowledge of and understanding about chemical ideas from the course content. On the other hand, the second part of the course does not seem to have had any impact on either students' knowledge of, or their understanding about the chemical ideas from the course's content.

In terms of students' misunderstandings, the applied independent learning approach, either from the first part or the second part of the Macromolecules course, does not seem to have positively affected students' responses. Whilst there was no statistically significant improvement in the student responses with a sign of misunderstanding in seven questions, in one question there were more statistically significantly responses after the Macromolecules course. This result can be interpreted as that independent learning approaches in certain settings may lead to an increase in the number of students' misunderstanding. This shows that the use of independent learning strategies needs careful handling.

Furthermore, the positive effects of the independent learning approach applied in the Macromolecules course on the students' intellectual attributes were seen in their scientific reasoning and their creativity to generate solutions to chemistry-related problems. This research study, on the other hand, has failed to detect any impact on students' self-assessment ability.

The merits and disadvantages of an independent learning approach to the subject can be considered from the data presented above. It appears from the findings presented in this chapter that the two parts of the Macromolecules course, although both parts aimed to promote independent learning, had completely different impacts on students' knowledge and understanding. These results and their implications will be discussed in detailed in Chapter 8.

Chapter 7: Students’ Views of the Macromolecules Course

Introduction

The Macromolecules course is the only example of a course which primarily relies on independent learning in the chemistry department in which this research study was undertaken. Considering the variety of non-traditional features of the Macromolecules course compared with other courses which students take in the department and the established lack of research into students’ views of the independent learning approaches, the investigation of the students’ views of the instruction strategy applied required closer attention. For this purpose, a short questionnaire with four open-ended questions was given to every student taking the course, followed by interviews with twenty-four of them to explore their responses in more detail and with a close focus on independent learning. This chapter presents the findings of those questionnaires and interviews.

According to the leader of the Macromolecules course, Professor X, “As well as teaching students what we know, it is becoming increasingly important to teach them how we think. We must take a scientific approach to science education and experiment with teaching methods, including context-led work and media-rich resources, to foster active and independent student engagement”. The Macromolecules course is the product of this experimentation with a scientific approach in chemistry education and is intended to foster active and independent student engagement as well as improving students’ knowledge of and understanding about polymer chemistry. In the department of chemistry in which this research study was undertaken, there have been significant attempts to gather data on the impact of the teaching approaches employed. The majority of those attempts encompass feedback about all the courses in general rather than measuring the impact of a specific course, and overwhelmingly these feedback forms generate quantitative data which usually do not allow drawing detailed conclusions about a particular teaching approach. Feedback collected in quantitative form can be very descriptive, personal and in many senses valuable, mainly due to the advantage it gives in analysis and application. However, it could be said that this kind of feedback collected usually fails to provide specific data about particular features and instruction strategy of the courses. So these data on their own cannot be particularly useful either in terms of improving the courses accordingly, or in terms of systematically monitoring the students' experience and perceptions of the instruction strategy. It became apparent that in order to address the research question posed in this study, and also to generate rich feedback on how the Macromolecules course could be improved, a questionnaire with open-ended questions followed by interviews would be appropriate.

The questionnaire and interviews were carried out after the students had completed the course and just after their tutorials, between 3 and 10 May 2012. Questionnaire forms were given to 176 students after their college tutorials about the Macromolecules course and they were asked to complete and return them in their own time. Eventually, 167 students returned a completed questionnaire and 24 of these were interviewed. More detailed information about the questionnaire and the interviews can also be found in the methodology chapter (see Section 4.2).

7.1 Instruction Methods which Help to Develop Knowledge and Understanding of Chemistry

The students were asked to evaluate their overall experience in the Department of Chemistry in terms of the contribution which the courses made to their knowledge and understanding of chemistry by defining the features of the courses. They were asked to state three features of the chemistry courses which they believed had contributed the most to their knowledge and understanding of chemistry. Figure 7.1 shows how many times each feature was mentioned by the students.

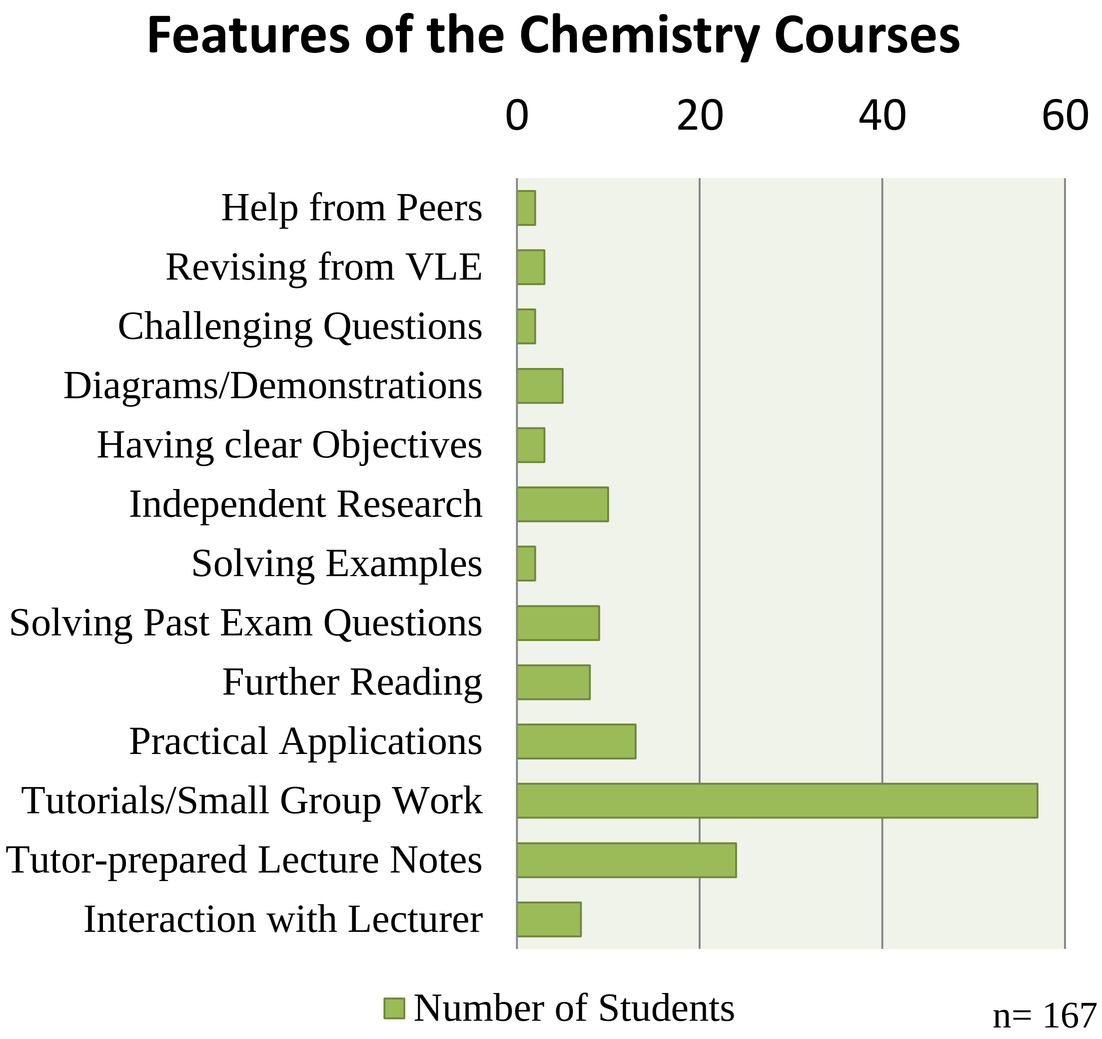


Figure 7. 1: Features which had Helped Students Most to Develop Their Knowledge and Understanding of Chemistry

Overall, tutorials were found by the students (34%) to be the most useful feature of chemistry courses to develop their knowledge and understanding of chemistry. Following this, they thought that having tutor-prepared lecture notes (14%) and practical applications (8%) such as laboratories had helped them to improve their knowledge and understanding of chemistry. After those three features, the main feature of the Macromolecules was ranked fourth, with 6%: ten of the 167 students who completed the questionnaire claimed that having to carry out independent research had significantly contributed to their knowledge and understanding.

There were clear indications that the students had benefited from tutorials after courses in numerous ways. There were many arguments for tutorials' contribution to their knowledge acquisition and understanding. It became apparent that working in small groups with discussions was considered by the students to be the most beneficial instruction strategy, but they also indicated that those discussions should be guided by appropriate lecturers.

> *Tutorials are the best thing to increase understanding and I enjoy working in a small group. (Student 136)*

> *Tutorial [allows you to] work with other people, talking about the topic and going through questions in depth with small groups. (Student 150)*

> *Tutorials are great for understanding as they focus review of the topic just after it is completed. (Student 12)*

> *Tutorials reinforce the key ideas very well. (Student 65)*

A sense that their knowledge and understanding had developed after tutorials was evident among most of the students. They thought of tutorials as an opportunity to ask the questions in their minds, and discuss the issues which emerged, with their peers in small groups. Whatever the initial learning style is – either traditional lecturing or independent learning strategies – after this initial stage, many gaps and questions seemed to remain in students' knowledge or understanding. Tutorials were seen as an opportunity to fill these gaps and find answers to those questions. It could be said that the students' insecurity with regard to the initial learning played a major role in the success of tutorials, as the students claimed that they could 'consolidate' their knowledge and understanding with the help of tutorials.

> *Tutorials: a chance to ask any questions in a small group/personal environment. (Student 42)*

> *Tutorials [are] for cleaning up problems. (Student 109)*

By doing the tutorials, [we] consolidate what we have learned. (Student 41)

Whilst the majority of the students found tutorials to be the most helpful feature of the courses, there was also a significant number of students who stated their appreciation of well-designed hand-outs. Apparently, the students found note-taking during lectures quite time-consuming and distracting, so having lecture notes which cover all the content of the courses helped them to work at their own pace and maintain their focus on the subject. They claimed that having tutor-prepared lecture notes was the second most useful feature of the courses which helped them to develop their knowledge and understanding of chemistry.

The study pack gives 'gold' chemistry information and helps with note-taking, good explanation of chemistry helps you to focus. (Student 103)

Style of hand-outs in most lectures allows you to absorb the information more, rather than spending time in taking or copying notes. (Student 79)

Concise notes are best for understanding as they allow you to focus on the content. (Student 16)

One student, on the other hand, was surprisingly unhappy at being given tutor-prepared lecture notes, and argued that re-writing lecture notes is very helpful as it gave her/him the opportunity to read through everything all over again.

Lectures with no/very basic hand-outs are beneficial as writing up these lecture notes neatly later on forces you to read through them. (Student 84)

Practical applications were also picked out as an important part of the courses to develop knowledge and understanding; however, they were usually seen as complementary to the other features of the courses rather than as a single, discrete component.

Labs: complement work done in lectures, but only good if they are based on a lecture course already completed. (Student 56)

Practicals that allow us to visually 'see' the chemistry we have learned [are the most useful feature of the courses.] (Student 31)

Practical works strengthen our understanding, we see it ourselves. (Student 125)

The unique feature of the Macromolecules course among all the other courses in the department was that it was instructed via independent learning. Particular features of the independent learning were mentioned rarely by the students in the questionnaire. Independent research was chosen as the most useful feature of chemistry courses to develop their knowledge and understanding of chemistry by ten students. Their arguments for their choice were mainly around the claim that they found the area they investigated more interesting than others.

Independent learning: I have learned the most as it was the most interesting for me. (Student163)

Writing the article helped build my interest in the topic. (Student 26)

Finding material for myself was the most beneficial, it was more interesting. (Student 97)

It can clearly be concluded that a small number of students (ten out of 167) thought that working on their own in independent research as an independent learning strategy was a particularly useful way of developing their knowledge and understanding of chemistry. The overwhelming majority of the students (157 of the 167) did not put independent investigations in their top three features of chemistry courses which had helped them to develop their knowledge and understanding of chemistry. In the students' view, a course that would develop their understanding of chemistry should involve lectures in which the relevant explanations were given by trusted, role-model lecturers who are experts in their field, that lectures should be followed by tutorials in which they can fill the gaps, find answers to their questions and consolidate their learning, and that those two techniques should be complemented with some practical work for visualising the theoretical knowledge. Independent investigations, on the other hand, were considered as particularly contributing to knowledge and understanding by only a few (ten) students.

7.2 Instruction Methods which Make Courses Enjoyable to Study

In order to gather useful data about the impact of the employed instruction strategy in the affective domain, the students were asked to describe the features of the courses which made them enjoyable to study. Figure 7.2 shows how many times each feature was mentioned by the students.

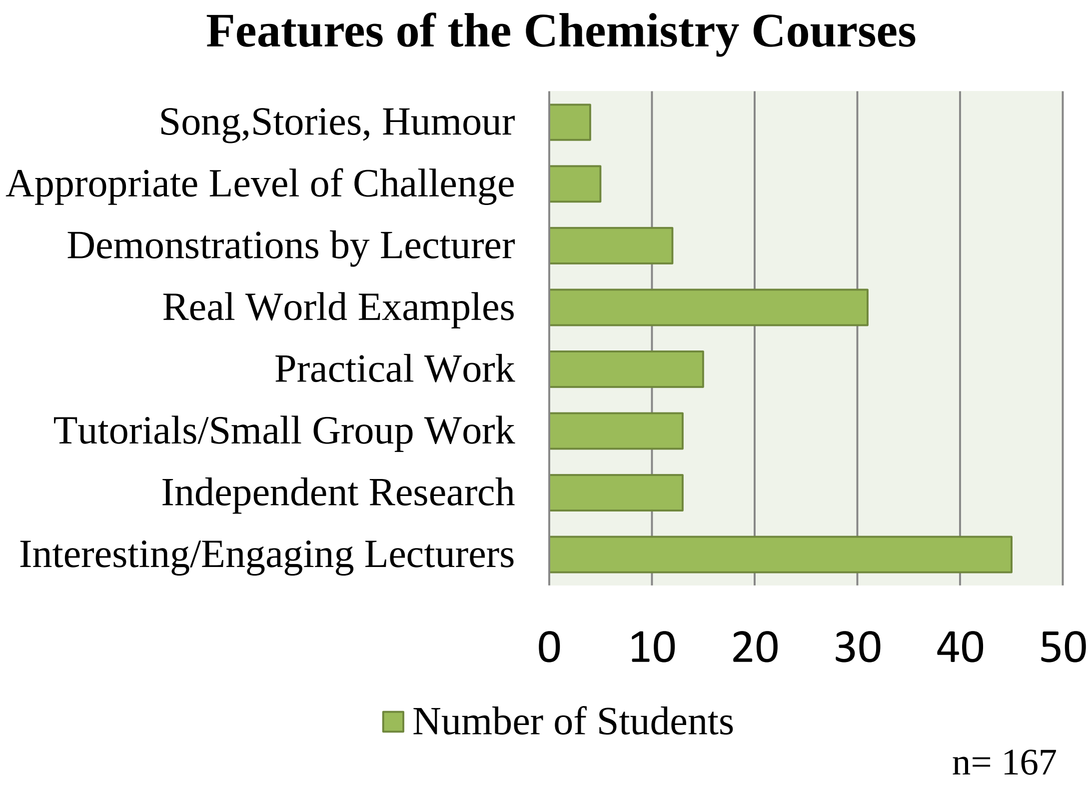


Figure 7. 2: Features which Make Courses Enjoyable to Study

As can be seen from Figure 7.2, lecturers were chosen as the most significant factor to make a course enjoyable. In the responses, there was a significant emphasis on the communication between lecturers and students, and the enthusiasm and keenness of the lecturer. It is very clear from the responses that the significance of the lecturers in terms of making a course enjoyable was vital.

> *Good lecturers always find ways to make courses enjoyable. (Student 121)*

> *Some lecturers really try to make lectures enjoyable/want to make you remember everything. (Student 166)*

> *Enthusiastic, motivational lecturers ... [make chemistry courses enjoyable]. (Student 22)*

The second most dominant feature of the chemistry courses that made them enjoyable was the real-world examples of the content. Contextualisation of the information given during the courses seemed to give students a 'need to know', a motivating factor which was broadly enjoyed.

> *Relevance to everyday life [makes courses enjoyable]. (Student 76)*

> *[I enjoy courses] when there are real-life everyday applications. (Student 51)*

> *Being told applications of the topic [makes courses enjoyable]. (Student 143)*

> *If the course, or parts of it, is related to everyday life [it is enjoyable to study]. (Student 87)*

These findings show similarities with the findings of other research studies in context-based education (Bennett *et al*., 2007; King, Bellocchi & Ritchie, 2007). Three main aims of context-based education, particularly in higher education settings, can be discerned from the literature: to provide students with more interesting lectures, to improve the science learning process by increasing the engagement which is stimulated by the increased interest in science and lectures, and to produce scientifically-literate people who can make sense out of some of the science which is related to their everyday lives (Bennett & Holman, 2003). The findings of this current study also show that context-based instruction makes chemistry lectures enjoyable to study for students in tertiary level chemistry education, which in turn increases their engagement and learning.

An interesting point to make here is that neither interesting lecturers nor real-world examples were considered by students as one of the three features of a course that would most help students to develop their knowledge and understanding of chemistry. Similarly, tutorials and well-designed lecture hand-outs were not considered to be one of the three features which will make chemistry courses particularly enjoyable to study. Looking at the literature on context-based education in chemistry, it can be concluded that previous findings in terms of students' understanding of particular ideas and their knowledge acquisition are relatively less significant compared with findings regarding students' engagement and interest. The findings from this current study show that students' self-assessment of their own knowledge acquisition and understanding present a direct correlation with the findings in the context-based education literature.

Furthermore, it is quite evident that what made a chemistry course enjoyable to study for the students who submitted questionnaire responses was strictly dependent on the instructor. The responses clearly indicate that personal differences between lecturers played a crucial role in the students' engagement with the lecture content.

> *Motivational and enthusiastic lecturers make courses interesting and enjoyable, lecturers who actually interested in lecturing you rather than the attitude of those just turn up to talk. (Student 4)*

As has also been discussed in the literature, context-based education is commonly criticised for making personal differences more apparent, which may have detrimental impacts on education systems (Vos *et al*., 2010). Although not being real evidence, student anecdotes from this current study support the argument that context-based education in chemistry might make the personal differences between lecturers more apparent.

After the factors that were directly related with instructors, the students said that social interaction was the factor that made chemistry courses enjoyable to study. Practical work and tutorials with small-group discussion were described as being significant factors for improving students' engagement with chemistry courses.

> *Being able to study and help each other with questions as trying to make someone else understand it helps you to understand something better yourself. (Student 132)*
>
> *Social aspects of working with other students [makes courses enjoyable to study]. (Student 42)*
>
> *Tutorials and Practicals: meeting all the new people on my course to discuss work etc. [makes courses enjoyable to study]. (Student 47)*

The main features of the Macromolecules course ranked after lecturers and social interactions as a factor which made chemistry courses enjoyable to study. Only thirteen students of the 167 respondents claimed that independent research in itself made a course enjoyable to study.

> *Independent research on a topic [makes courses enjoyable to study]. (Student 8)*
>
> *I think independent research like Macromolecules course makes [courses enjoyable to study]; it helps you to see how useful chemistry is. (Student 71)*

The uniqueness of the independent learning approach in the department appeared to be the most common reason for students to nominate independent research as a factor which made courses enjoyable to study. It was 'doing something different from all the other courses'. The novelty of the instruction strategy seemed to be the predominant reason for students' decision to name it as a feature which made a course enjoyable to study.

Doing something different to normal [makes them enjoyable to study] e.g. the Macromolecules course. (Student 148)

Varied approaches among the courses [makes them enjoyable to study] (i.e. independent learning style). (Student 103)

Being able to investigate and present the work [makes them enjoyable to study] e.g. like the videos for Macromolecules. (Student 36)

However, there were very few students who mentioned discovering 'new things' through independent research.

Discovering things in independent study [makes them enjoyable to study]. (Student 53)

To conclude, it can be seen from the results that a small number of students (13 of the 167) put the instruction strategy applied in their list of three factors which made a course enjoyable to study. For the students who thought so, the main reason for their decision was the differentness of the instruction approach. It can be concluded from the results of the questionnaire that the majority of the students did not think that the independent learning approach is a strategy which makes a course enjoyable to study. In the students' responses, the significance of the lecturer and the social interactions were apparent. The responses collected in this research study have shown similar themes to the findings of previous research studies in the literature of context-based science education.

7.3 Rankings of the Macromolecules Course

In order to evaluate the effectiveness of the employed instruction strategy compared with the instruction strategies used in other courses, the students were asked to give the names of the courses which had particularly helped them to develop their knowledge and understanding of chemistry. Figure 7.3 shows the ranking of the courses named by the students as helping them to develop their knowledge and understanding.

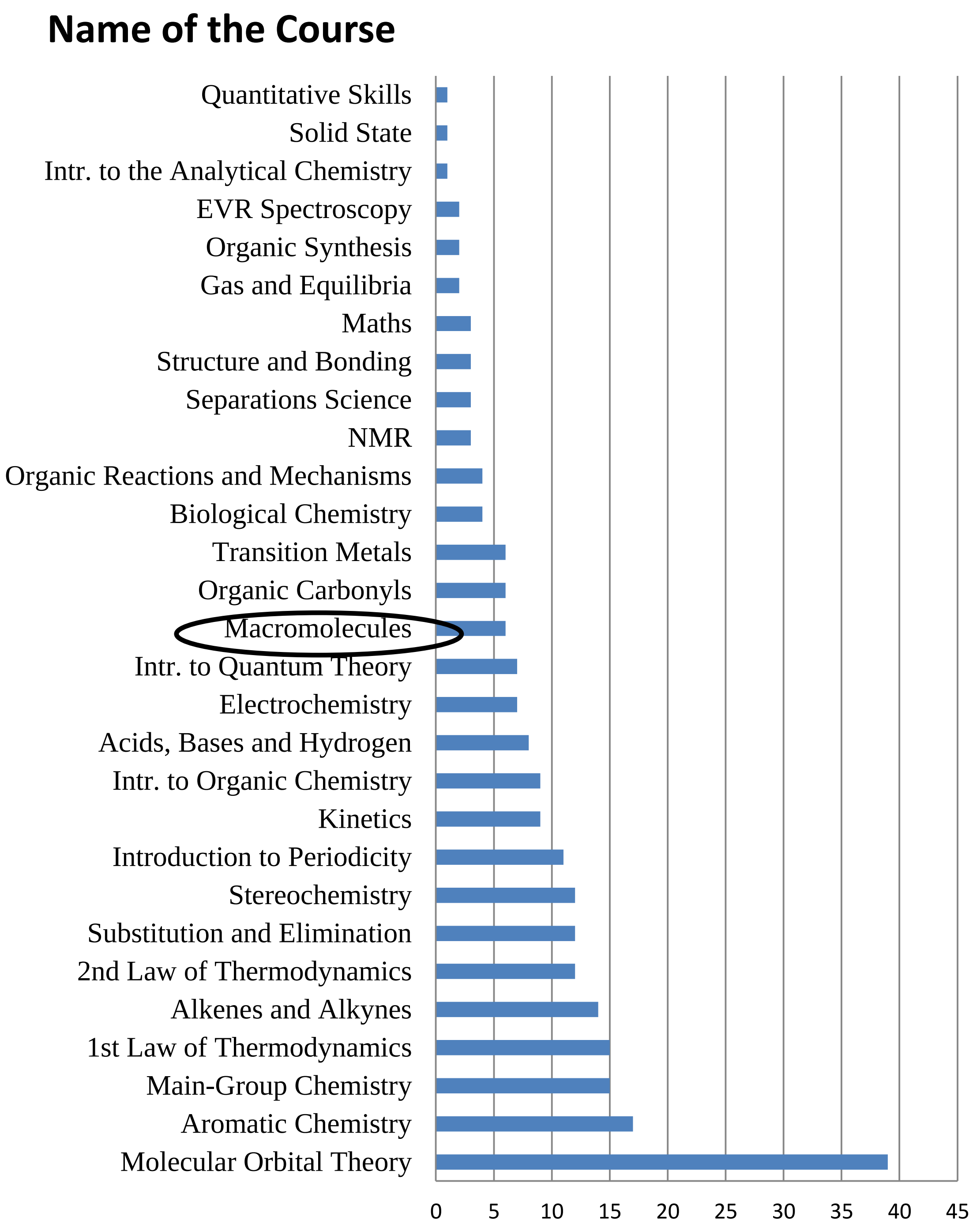


Figure 7. 3: Rankings of the Courses that had Particularly Helped Students to Develop their Knowledge and Understanding

Figure 7.3 shows that six of the 167 students said that the Macromolecules course was one of three courses which particularly helped them to develop their knowledge and understanding of chemistry. The molecular orbital theory course was picked by most students. One interesting point to note from this finding is that the molecular orbital theory course is one of the most theoretical and the most traditionally instructed courses in the department, and that it has a strictly guided instruction strategy. The two following courses of aromatic chemistry and main group chemistry are instructed using similar strategies. It can be interpreted from these data that the more traditional teaching strategies were perceived by the students to be more effective at developing their knowledge and understanding of chemistry. Another reason for the high ranking of some of the courses may be their content. Some courses' content may be perceived by the students to be more effective at developing their knowledge and understanding of chemistry.

In a very recent research study, researchers found that students' perceptions of their own learning and an instructor's effectiveness appeared to be based on lecture fluency and not on actual learning (Carpenter, Wilford, Kornell & Mullaney, 2013). According to that study, when a presenter was seen to handle complicated information effortlessly, students sensed wrongly that they too had acquired a firm grasp of the material.

Carpenter (2013) and her colleagues showed 42 undergraduate students a one-minute video of a science lecture about calico cats. Half of them saw a version in which the lecturer was confident, eloquent, made eye-contact and gestured with her hands. The other students saw a version in which the same lecturer presented the same facts, but did so in a fumbling style, frequently checking her notes, making little eye-contact and few gestures.

After watching the video, the students rated how well they thought they would do on a test of its content ten minutes later. The students who had seen the smooth lecturer thought that they would do much better than did the students who saw the other lecturer, consistent with the idea that a fluent speaker breeds confidence. In fact, there was no statistically significant difference between the students' subsequent success at this test. Obviously, the most important limitation of that study is that the students only watched a short video of the presentation and it is questionable whether students would give same results in real contexts and after longer lectures, but looking at the recent findings it can be claimed that students' perception of their own learning stems from the instructors' effectiveness rather than their own actual learning. Drawing a parallel from that research study, it might be the case that students do not consider independent learning strategies as strategies in which they particularly develop knowledge and understanding since the instructor has a smaller role during independent learning. Actual development of students' knowledge and understanding under the independent learning strategy which was applied in the Macromolecules course was presented in Chapters 5 and 6.

The instruction strategy applied in the Macromolecules course was not regarded by the students as a particularly helpful way to develop their knowledge and understanding of chemistry. On the other hand, the ranking of the courses which they found the most enjoyable to study reveals a completely different picture than the ranking of the courses which students found particularly helpful for their understanding of chemistry.

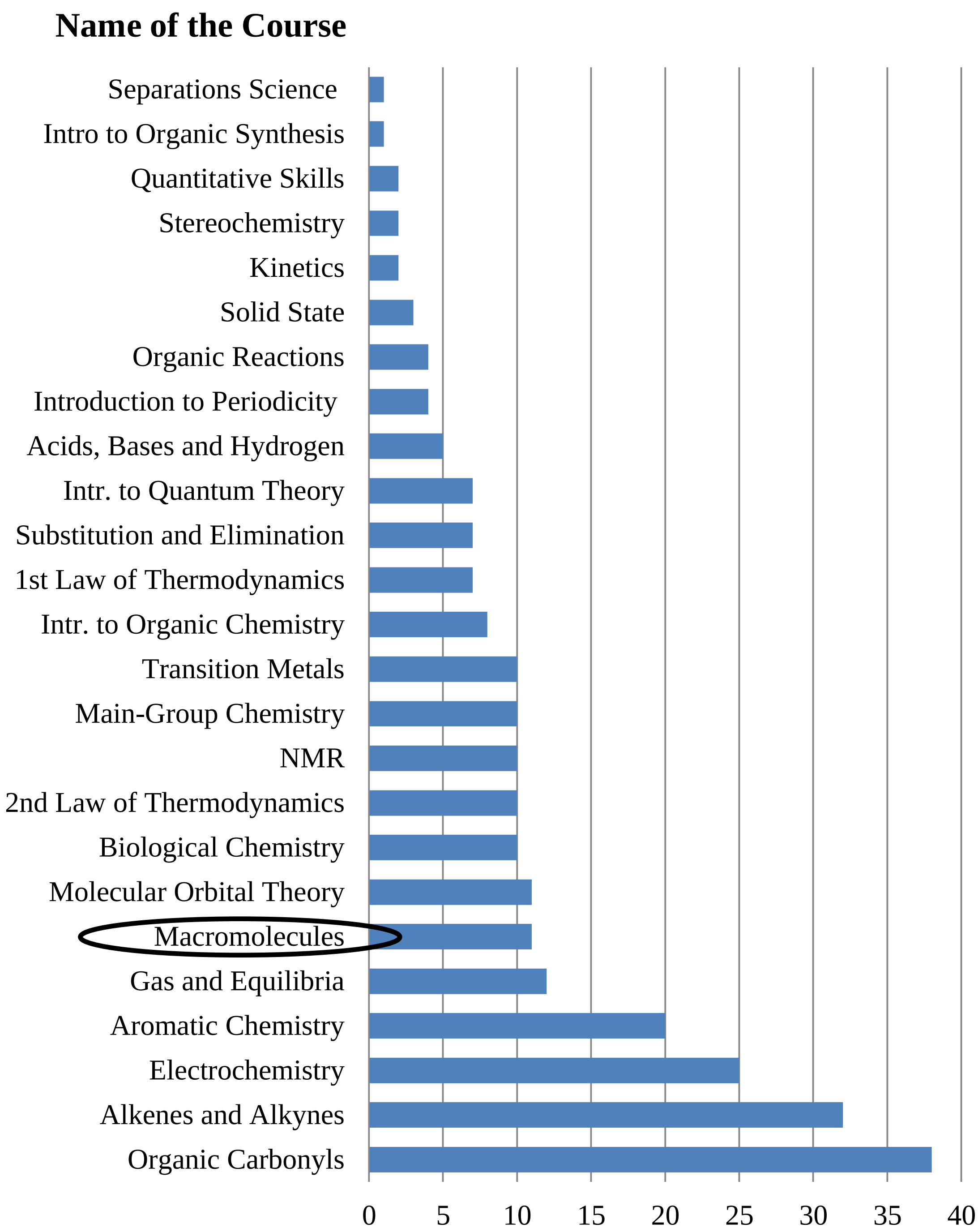


Figure 7. 4: Ranking of the Courses which Made Studying Enjoyable

As can be seen from Figure 7.4, the most enjoyed three courses were organic carbonyls, alkenes and alkynes, and electrochemistry. The main reason for the students' choices becomes apparent from their comments, which often referred to the names of the individual lecturers.

Prof. X's lectures, he is my hero!! (Student 166)

Whatever Prof Y. does it works, he is just amazing. (Student 74)

Dr Z's courses were great, he is so funny. (Student 30)

It seems that the students had preferences for the instructors more than for the instruction strategies or the lecture contents when they judged the success of the courses at making them enjoyable to study. Prof. X was the lecturer for the electrochemistry course, Prof. Y for alkenes and alkynes, and Dr Z for the organic carbonyls course.

It is quite surprising that the courses in which the students believed that they had particularly improved their knowledge and understanding of chemistry were quite different from those which they described as enjoyable to study. The courses which they found enjoyable to study were usually the courses which were instructed using the context-based approach. They included a variety of demonstrations, everyday-life examples and some element of humour and they were all facilitated by lecturers who had a particular interest in context-based education. However, those courses were not considered as courses in which the students particularly developed their knowledge and understanding of chemistry. On the other hand, courses which were instructed with relatively strict guidance in a more traditional manner were considered by the students as courses in which they particularly developed their knowledge and understanding of chemistry. It is clear that this result was generated by the students' perception of their own learning; however, the employment of more robust methods of recording the correlations between students' perceptions of their own learning within different instruction approaches and their actual learning is a possibility for further research.

The instruction method applied in the Macromolecules course was considered to be an effective way of making a course enjoyable to study by 11 of the 167 students. This proportion is quite small compared with those for other courses. In order to investigate the principles of the instruction method for the Macromolecules course and students' view of it in detail, 24 students were interviewed. In the next section, the data generated from the interviews with these students will be discussed.

7.4 Student Interviews

After reporting some general findings from the data generated by the student questionnaire, in this section the data generated from the interviews with 24 students will be discussed. The aim of the interviews was to generate data specifically about the Macromolecules course and the independent learning strategy employed in it, unlike the questionnaire which provided more general data involving other courses taught in the Department of Chemistry. Detailed information about the interview design, sampling, administration and analysis was given in section 4.2.7. In this section, the data generated through interviews will be presented and discussed.

Overall, the reactions of the interviewees to the Macromolecules course could be characterized as positive. More specifically, they indicated that they "appreciated the attempt to change the routine of university teaching" (19 of the 24 students), that they "discovered new things" (14 students), and that they "had a chance to see an improvement in their chemistry knowledge and understanding" (12 students). Also, a number of the interviewees suggested that their perception of studying chemistry had been changed by their experience during the Macromolecules course, stating "I shall never study a course in the same way again" (4 students). Furthermore, a small number of interviewees indicated that they were "bored" (1 student) or "confused" (3 students) by what they came across in the introduction lecture of the Macromolecules course.

It became apparent that the students were not accustomed to a course in which only independent learning strategies were employed, which had made their experience more exciting due to the fact that it is unusual and the method is relatively unexplored. Some typical responses can be seen below.

Well, we have always been used to doing a series of lectures, you know, six or eight lectures then you go home, do some tutorial questions, go to the tutorial then it is done, but then this was completely different that with this block hand-out, you are teaching yourself then doing the investigation and presentation, and do some questions that will affect your end of year mark. It was really a different experience. (Student 53)

I, myself, liked the independent learning aspect because it made me feel that I have done something different rather than sitting in a lecture and stuff like that because in lectures I do not feel motivated to do anything else than what the lecturer gives (Student 71)

... it was completely different and exciting for me. (Student 152)

it was a nice change really. (Student 118)

7.4.1 Students' Appreciation of the Macromolecules Course

The instruction strategy applied in the Macromolecules course was appreciated in general by the majority of the students (18 out of 24) interviewed. The reasons for their appreciation of the teaching approach varied.

7.4.1.1 Contribution to Independent Learning

There were clear indications that the students appreciated the Macromolecules course as they believed that its instruction strategy was a beneficial way to improve their independent learning abilities. Students were not able to define or describe specific abilities which they consider as independent learning ability. However, they thought that they would have to adapt to the independent learning style as during their university education and beyond, this will be the most predominant learning strategy that they will use.

I think it is something like maths for me. ... for maths at first I really did not want to do in A levels, but I thought it was carrying on with my other choices, and eventually when I passed it, I suddenly realised that I started using maths like in many other courses, like independent learning really. So, maybe in the future I can sort of teach myself using independent learning. (Student 14)

In my school there was a lot of emphasis on, you know, independent learning, because that is what you have to do in the university anyway. (Student 53)

I think that self-teaching is always quite good really, I think it can be really beneficial and I think it is very important at degree level because, obviously, the degree is a point that people kind of stop holding your hand in education as you like. I do think that it is really important for life skills when you get outside of your degree. (Student 71)

As can be seen from these comments, the Macromolecules course was seen by some students as a way of developing their independent learning skills. They believed that these skills would be very useful for them during their tertiary-level education and beyond. However, there was no specific example of independent learning skills described by the students that they had started using. The use of the words ‘independent learning skills’ was quite loose and the majority of the interviewees seemed to have fundamental problems about understanding what independent learning skills are or how to use them.

7.4.1.2 Knowing What People do not Know and the Sense of Superiority

Among the interviewees, there was a significant appreciation of being able to work at their own pace on a topic that they had chosen, and of creating something on their own. They thought of the Macromolecules course as an opportunity to study whenever they want to study, to find out about a topic that they are personally interested in, and to learn about the issues that they believe they will face with in the future. The majority of polymer chemistry still remained unknown and mysterious as a domain for the most of the interviewees, but the Macromolecules course was seen as an unusual and rare experience offering them a sense of privilege. It gave them an opportunity to be different, followed by a sense of superiority over other people (including their peers and lecturers) who do not study the same topic. This feeling of superiority seems to be a significant motivation for the students to sustain their focus on the topic during independent learning activities which in turn suggests that they would not be able to be motivated if they were given a topic that they were not particularly interested in and asked to work on it under similar instruction conditions.

> *I showed my video to my friends doing chemistry, proudly they really liked it. (Student 163)*

> *I did quite enjoy it actually. You know, going off and looking into something, you know we have got to choose the titles about articles, I chose the one that interested me the most and I really enjoyed going off and finding more information about it and I enjoyed presenting my findings because I do like ... imparting knowledge to others. (Student 141)*

> *I think it is really interesting because you find out things that people don't know. I remember our tutor who was running the workshop said he learned things from what people have said in their articles, which I thought was really interesting; he has such a high level of education in chemistry obviously, but even he was learning things from us. (Student 103)*

> *I think at the time I did not realise that I was enjoying it, but then suddenly I started like telling my mum about the polymers, well, I have been telling her because I was actually interested and enjoying learning about it. (Student 118)*

7.4.1.3. Being a Researcher and the Sense of Discovery

Six students seemed to enjoy the feeling of being a researcher and managing their own investigations during the Macromolecules course. They claimed that they had discovered a great deal of knowledge on their own which had broadened their vision of chemistry. They also claimed that they had understood the complexity of polymer chemistry and enjoyed the challenge and controversy of different approaches and ethical considerations in chemistry as opposed to the assumed dogmatic structure of chemistry.

I think also being a researcher, like having to find stuff to write about, that was, like looking for the different; it helps a lot to see how much stuff there is out there about polymers. (Student 8)

I really liked it in the sense that I picked a topic that I was really interested in and made the research, I went and read about it and I was even more interested in it at the end. (Student 163)

I have always been interested in chemistry, I really enjoyed it and still enjoy it, I would say when I was researching, I have been reading one article and carrying on to another one, it sends you to another, and it grows and grows, and it did make me realise how vast the chemistry is, that is definitely something positive for me that I am quite excited about so that was a bit of a realisation. (Student 41)

I really enjoyed searching for the knowledge when I was searching for my presentation. I discovered many things that I didn't know. (Student 97)

7.4.1.4 Learning more than in a Traditional Lecture

Four of the interviewees compared the teaching approach of the Macromolecules course with the traditional lecturing style. As a result, they claimed that they had learned more under the independent learning strategy than in other lectures. Their argument was that they did not have enough time to pay attention to the crucial points during lectures so they could not achieve a deep understanding of the topic in traditional lectures.

I really prefer that sort of style; I do not particularly think that the lecturing style of teaching is working for me personally. I usually cannot pay the utmost attention during the lecture, I sort of tend to get the notes down rather than thinking about the course content. (Student 141)

At the personal level, I would definitely prefer that. In chemistry, every course could have been taught like that, it does not depend on people's opinion, it is not like that. Anyone who sort of read the book enough, you don't need to be a doctor of chemistry, can learn it. It is not like philosophizing issues under discussion, I think for the first-year chemistry courses that I have taken, all could have been taught in the independent learning style of teaching rather than lecturing. (Student 97)

Moreover, there were two students who claimed that they had been doing this sort of learning for all the courses. They said that it was much harder to work on in the other courses as the information that needed to be learned was not very clear and it was hard for them to find a particular piece of information. They claimed that in the Macromolecules course, they enjoyed the way the course was set out and especially the interactive booklet and personal investigation. They stated that information was presented in a clear and engaging way, which encouraged further exploration of the subject, as opposed to the information that they usually received in traditional lectures. They claimed that even in the most 'effective' traditional lectures, they were not learning during the lecture but that they were teaching the course content to themselves later on.

I have not been paying a huge amount of attention in the lectures really, I just sort of would take the notes down and get the questions sort of, but I wasn't listening really, I was just keeping all the information and then I was reading and trying to teach it to myself. And the Macromolecules course was like giving me that knowledge that I had to go through and I tried to teach it to myself. So, I felt that I have already been doing this but it was much more painful for me to collect that information from lectures and staff. (Student 71)

7.4.2 Students' Problems with the Macromolecules Course

There was a relatively small number of students among the interviewees (8 of the 24) who had struggled with the independent learning strategy applied in the Macromolecules course. The interviews with those students revealed a variety of reasons behind their discomfort with the instruction strategy applied. Next, those reasons will be discussed and related extracts from the student statements will be presented.

7.4.2.1 Independent Learning Requires Too Much Time and Effort

The most significant theme among the negative features which the students commented on in the instruction strategy was that this type of instruction strategy requires too much time and effort from students. As discussed in Chapter 3, one of the main reasons behind the creation and application of the independent learning strategies was the shift in the student profile. It was suggested that students seem to have developed some independent learning styles due to the time they spend in front of a computer, seeking and retrieving information from the internet, which marks a striking contrast to previous generations of students, who tended to acquire information more passively from authority figures. However, the data generated by this current research study imply that this shift in the student profile also includes features such as impatience and a lack of interest in searching for information which is not easily found within a very short time, as students' interest and inquiry do not last long. This might be due to the argument which claims that students' span of interest and motivation in searching for information decreases with the use of internet. Hence, some of the interviewees stated that this type of instruction strategy is heavily demanding of time and effort compared with more traditionally instructed lectures.

> *I spent a lot of time to think. It took me quite a lot of time. I started getting information and then write, but it still doesn't look good, it still doesn't look enough. Do you know what I mean? Trying to edit it, oh no, I don't need that bit, this part I should be adding more. I was kind of getting bored of working for it. (Student 84)*

It is good to have one [lecture taught in this type of instruction]; I think, if we had everything [like that] then it would be quite a lot of work, I would say. Some courses are just better to be taught by a lecturer. The only thing that I am concerned with this course is that sometimes you can understand better when the lecturer shows or people ask questions. It is not easy to look for an answer to every question that you have in mind. (Student 84)

But I don't know, in some ways it did feel a little bit like strange. ... you can't just go and ask your lecturer; in other lectures you could just go and ask someone which would take seconds, but in this you kind of had to look for it, which might take ages as you read something else then something else, it was a bit annoying. (Student 90)

7.4.2.2 Problems with the Sense of Authentic Discovery

In the literature on instruction strategies which aim to promote independent learning, authenticity of inquiry is one of the most commonly argued topics (for example, Lee & Butler, 2003). Some students argued during the interviews that they did not feel that their investigation was authentic as they were looking for a piece of information which had already been discovered and they just needed to go and find out about it. Their perception was that since it has already been discovered and their lecturers know about it, the most sensible way was to be taught by their lecturers. They related the authenticity of investigation with the discovery of a piece of information by mankind in general rather than the discovery of a piece of information by themselves.

I don't know why exactly that would be different but it felt like useful things that I can go and do had already been done by others; it had sort of little purpose, it was kind of like, why do I have to go and answer this little question? It could be just said or explained there, it is already known after all. I was like thinking for a minute and then doing those entire searches like Wikipedia, that sort of thing out there, but it was not like real. (Student 14)

It seemed very straightforward on the internet, well, that is the fact. I could have done more maybe something could have been useful was that to find out in a more meaningful way about the most of the things would have probably involve looking at actually scientific papers. Then, I could have discovered things, though it would have taken ages. But like that it was a bit like, you know ... (Student 93)

I don't know, some of them was interesting but otherwise it kind of felt that I was just trying to fill out the answers. Maybe it is all because of the situation that you are aware of the fact that the answer exists, someone has already done it somewhere and so what you are doing is more trailing around, not like discovering. (Student 111)

The interviewees' descriptions of authentic investigation did not involve researching a topic given by their lecturers. Authentic investigation was defined by the students as looking for an idea that they had come up with on their own.

If it had been entirely my own idea, I would have found it extremely entertaining. Because it is something entirely came up to my mind and I want to find this out, and I can see that would have been interesting, you know probably have done it in some occasions. But that was not the case in the Macromolecules course. (Student 57)

7.4.2.3 Lack of Interaction with Other Students and Lecturers

Eighteen students stated at some point during their interviews that interaction with people was very important for them to improve their interest in the topic that they were studying. Because of the fact that the Macromolecules course was structured with an independent learning strategy and aimed to increase student autonomy, student-lecturer interaction was minimal. Particularly for the second part of the Macromolecules course, during which students did their independent investigation, there was no interaction between students and lecturers until students presented their findings. For some students, this lack of interaction appeared to be a negative factor on their interest in their investigation.

> *I don't know, maybe it was just the lack of interaction with an actual person, with anyone else, I was not sure why I was interested in finding out about it. (Student 106)*

> *I am not sure [if] not being able to interact with lecturers was a good idea. I do not feel it has affected my interest to chemistry positively. (Student 63)*

> *It was this lack of contact thing. I was not sure where or why I was looking at or why it was interesting. It was the whole independent learning thing was quite broad and I struggled to cope with that. (Student 14)*

As can be seen from the students' comments, they seem to be so connected to their teachers/lecturers that they lost their interest when they lost their interaction with their lecturers. This might be one of the reasons for the dependence in the science-student profile which is often mentioned in the literature. One of the common criticisms of today's higher education is that it cannot prepare students for the modern working environments in which they will find themselves in the future. A lecturer-dependent thinking and learning profile of the students has become apparent in this research study as well. Students who have this attitude seemed to struggle to adopt the independent learning approach and felt the lack of interaction both with lecturers and with one another deeply.

> *I was thinking like what makes a good serious lecture, this is for me anyway because I am more attached to a teacher always, what is it, as you know they come up sometimes with very different styles, and one of the things that I picked up from good teachers was that quite often they tell stories, in science a lot of these things are related to real life, and I think that usually works for me, I just feel too serious when I am [working] alone. (Student 63)*

Considering these ideas of students, it can be concluded that the lack of interaction between lecturer and students was considered obstructive. It has become apparent that since the change in the student profile, the appliance of independent learning strategies requires a gradual decrease (if it is needed) in the amount of interaction with the intention of increasing students' autonomy, rather than a sharp change. Some students seem to lose their interest in learning when there is a sudden lack of interaction with their lecturers.

7.4.2.4 The Interaction with the 'Needed-to-be-Learned' Knowledge is Hard

One of the common criticisms of instruction strategies which aim to promote independent learning in the literature is that they put greater pressure on students' short-term memory and thus increase the cognitive load (Mayer, 2004). From a traditional instruction perspective, reducing the extraneous cognitive load carried by the learner in processing knowledge can be achieved through more traditional instruction. Having students figure out the solutions with independent learning entails the greatest cognitive load, and so cannot lead to successful learning gains. Probably the main reason for this cognitive load in independent learning strategies is the fact that the students have to 'select' on their own – by attending to the relevant information that enters the cognitive system through their eyes and ears – the information which has to be learned. In constructivist learning theory, selection is the first of the three major cognitive processes (selecting, organising and integrating) of the learning phenomenon. Six students stated that they struggled to make contact with the to-be-learned information during their investigations.

> *... you don't know what the limit is, what you are exactly supposed to learn is, do you know what I mean, whereas other lectures they tell you "you need to know this", but when you are an independent learner you don't know where the limits are, I found it very difficult to examine what I should have learned, how much. (Student 90)*

Even people, you know, in the highest job positions in the country, if they go and start to do something new, I am sure they give them the basic groundings in work. I was not even sure what I was exactly needed to learn in my investigation. (Student 57)

I spent so much time in reading but I don't really know how much of it was really useful. It is really hard to keep your focus when you don't know what is the important knowledge, especially if you are searching on the internet. (Student 63)

Considering the fact that the intended learning outcomes and objectives of the course had been given to the students with their hand-outs right at the start of the study, it was expected that they would be able to know what they were expected to do. However, it became apparent that some students were not able to comprehend the intended learning outcomes, or they just ignored them. Their interview responses imply that explanation of the intended learning outcomes is required; merely providing a written presentation of the learning outcomes to them seems to be not enough for them to have full comprehension of what they were expected to learn during independent learning activities. Similar issues were found when students in problem-based learning (PBL) curricula in three different disciplines were interviewed, Dahlgren and Dahlgren (2002) found that students in two of three disciplines felt a great sense of uncertainty about what to study at the beginning of their courses. However in PBL settings, students' independent learning strategies evolve over time (Evensen, Salisbury-Glennon & Glenn, 2001).

7.4.2.5 Problems with Technology

Finally, some students thought that the course was unsuccessful because it involved technology which created many problems. Those students thought that expecting to achieve interaction and assessment through technology was not an effective way of learning. Although they complained about the technology-related features of the Macromolecules course, they were all aware that those issues could be ameliorated in time. They therefore considered those issues to be trivial issues in terms of the course.

I would say that the feedback on the VLE made it confusing us for to do what. Because there wasn't any feedback they just gave you a number, didn't tell you anything in any detail about what you have got wrong, and if you don't know what you have got wrong, you can't improve, until the tutorials it was quite annoying. (Student 57)

Staring at a computer screen – well, I would rather have an exam paper in front of me. (Student 84)

You filled in your answers and you did multiple choice answers or whatever, and you could not go back and check your answers and there were sort of handfuls of sort of quite lengthy calculations. If you later realised one of your mistakes you cannot go back and change it. (Student 90)

7.4.3 Impact on Students' 'Skill' Development

The vast majority of the interviewees (22 out of 24) claimed that they had developed some useful skills from the Macromolecules course. The skills which were described by students were independent learning skills, time management, research management, writing skills, IT skills and communication skills. Related quotes to illustrate these will be presented in this section.

Well, you definitely develop some skills and you develop new skills that you haven't done before, so actually that is a positive side. (Student 53)

7.4.3.1 Independent Learning and Research Skills

There were clear indications that the interviewees believed that they had developed skills which helped them to work independently. There were many comments related to their ability to find valuable information on their own, particularly in terms of selecting the required information from sources in which there is a massive amount of information, such as the internet.

I was really used to being, you know, 'spoon-fed' really, this is what I have been taught. Now, we have got to learn skills to learn by ourselves and I should say this course is a step towards it. (Student 163)

I think my scientific research skills did develop, like doing a research to write an article, I feel confident to do it again now, so that was probably the biggest gain really. (Student 41)

I suppose the key thing was the independent learning, there was much work that we had to do by ourselves, there was no tutorial that we normally would have, so we had to ask each other rather than relying on the staff, so ... I think that is a quite important skill, figuring out what to do on your own. (Student 148)

So, I think about it a lot more now like is this a right source or not, and also researching skills, using the internet and searching for the information. I go and check things on my own after lectures now. (Student 71)

A sense of discovery and intrigue was evident among most of the interviewees about their skill development during the Macromolecules course. They thought of the Macromolecules course as an opportunity to 'develop' some skills which they believed they would use often in the future. To find out how scientific researchers in the chemistry domain spend the majority of their time seeking useful knowledge through the internet, and learning about the advantages and disadvantages of being able to reach an almost infinite amount of information through the internet, seemed to be an experience that the students really appreciated. Being a 'researcher' was an unknown and mysterious phenomenon for most of them and the Macromolecules course was seen as an unusual and rare experience offering them a sense of privilege. It could be said that the students' lack of familiarity with this style of instruction played a major role in their appreciation of the Macromolecules course in terms of simple enjoyment.

... the self-learning skill, actually getting the knowledge that you needed to get. When you do have a computer in front of you, all the information is on the internet, you just need to know where to look. I struggled in the beginning but at the end I was more effective in finding out what I really need. (Student 103)

I think also being a researcher like having to find stuff to write about that was, like looking for the different, because when you are studying on your own you, you know where to go and find the information, like which site to use or how to find the publications. (Student 36)

I am pretty sure that I have improved [my skills] but it is just hard to say how much. It was just a nice change from, like, I don't know, like, being set rather than going and doing the same things it was actually something good to do. (Student 8)

Following the independent learning and researching skills, the skills which the students mentioned most were writing, presentation, IT skills and time management skills. Many students were excited about learning techniques that they would use in their future assignments and they claimed that they would be better at time management in their future assignments.

Writing the article thing was very helpful because of referencing and the things like that; it helps you to develop required skills which I will need often. (Student 41)

It has helped me, sort of, for the future projects; how to research, how to manage the time in assignments. (Student 150)

Well, probably time management, not leaving it to the last minute. I really couldn't appreciate how long the research was going to take me. So it has helped me in time management and, also, the resources out there for the research, it helped me to see what I could find out through my own access. (Student 155)

I did the video, I have definitely developed my IT skills quite a lot, which is actually quite good, so I can actually now sort of edit videos and upload that stuff; so that is one skill I am sure of. (Student 103)

A number of the interviewees claimed that their gain in skills was higher than their gain in knowledge during the Macromolecules course. This claim is quite interesting and is in line with the learning objectives of the Macromolecules course. As discussed earlier, the learning objectives of the course also included improving students' independent learning skills (*see* Table 3.2.4).

I think this course has helped me more in gaining skills than getting knowledge as we had already known a lot of the content about polymers from our A-levels. (Student 141)

I think the knowledge and skill that we gained was quite high, I mean, I learned the content as well but I think about my presentation and I can remember many of the things that I learned for my project, but not the booklet's content. (Student 26)

One significant point which was made by two interviewees was that they had learned the skills which they mentioned much better by trial and error. They said that it would not be as useful as the Macromolecules course if they had been given a workshop about those skills intended to be taught.

I think I learned skills better by making mistakes and looking at them by myself. If this was like a three-hour workshop, about this is how you reference, this is how you search, this is how you write, you know; I think I learned it better by doing it myself in terms of skills. (Student 14)

Furthermore, there were two other students who stated that they developed more generic skills such as video editing skills during the Macromolecules course rather than developing chemistry-specific skills.

> *Doing the video required a skill set, but in terms of chemistry, I don't think I developed any skills. (Student 106)*

7.4.4 Impact on Students' Views of Teaching and Learning in Higher Education

Considering that this type of instruction was quite unusual for the sample of students, the impact of the instruction strategy on their perspective of higher education was also investigated. As a result of this investigation, some interesting ideas emerged. The majority of the students (14 out of 24) thought that the Macromolecules course had an appropriate instruction strategy for teaching chemistry at tertiary level. On the other hand, the rest of the students thought that the course was inappropriate for teaching chemistry at tertiary level. They usually compared the Macromolecules course with other traditionally instructed lectures and they often used terms such as 'spoon-fed' or 'knowledge transfer' to describe traditionally instructed lectures. On the other hand, the Macromolecules course was usually associated with self-learning, independent learning or learning how to learn.

> *What teaching means shifted from lecturing to self-teaching for me. Preliminarily it was only teaching and now it is more like self-learning for me. Other courses do a little bit of self-learning as well, but they are mainly reading, that you are reading yourself. That [the Macromolecules course] was more like a whole process of self-learning. (Student 155)*

There were some students who claimed that they had learned better during the Macromolecules course compared with traditional lectures. Their reasons for this claim varied, but the main theme was that they studied something that they were interested in, enjoyed it more and learned more.

I think actually I know why I have learned more in that than the normal lecture courses, because in a lecture normally you don't have time to absorb what you are doing as you usually write down constantly I don't learn actually until the lecture course finishes. (Student 97)

I just enjoyed it more and when you enjoy you do learn it better. (Student 148)

I think people spend so much time to memorise things but you did not really need those in that course it was more about understanding. (Student 26)

I thought the topic was quite interesting also, I found that finding out the information helped me learn a bit better, or kind of taking it in a bit more. (Student 150)

I can remember a lot from my research that I have found out, because it was something that I have chosen to research so I thought yes, this is going to interest me, and you just absorb it more, don't you? (Student 71)

Some students were able to give specific examples of their improved metacognitive skills for learning. For instance, one student claimed that he had learned to self-assess the correctness of his calculations by looking at the units. He argued that he had developed this ability by learning on his own and that otherwise he would not have been able to acquire it.

It only tends to be things like, for example, say units; it has kind of revolutionized it, when you have got using the units and you calculate it, you can tell immediately if something is wrong, and sometimes you don't even need the equation, and I have realised this by learning alone. (Student 97)

Among the interviewees, there were also four students who stated that their way of studying had changed fundamentally with the Macromolecules course.

Well, I found myself after the course [in the] last a few weeks, going and looking at textbooks and reading around about what lecturers have told me more than I used to, I think that may be an effect of this project: I go and look around to make sure I understand the topic as a whole rather than only what the lecturers have told me. (Student 148)

On the other hand, the majority of the interviewees claimed that this course was a step towards improving independent learning. There was a clear sense that they had found the course very encouraging, but they emphasized that they definitely needed time to adopt this way of instruction to feel more comfortable with it.

I think we have been brought up in a way that teachers teach us, so I think it is going to take us quite a long time to move on to independent learning; this is like a first step as I have still got that image of lecturers coming and teaching me. (Student 63)

I think it encourages ourselves to going and finding out for ourselves rather than just listening to the lecturer maybe you can go off and research on yourself. But you need to get used to this. (Student 36)

7.4.5 Impact on Students' Interest

All of the students interviewed about the Macromolecules course found the course quite interesting and they said they had enjoyed doing it. As stated earlier, the main theme that emerged as a reason for their interest in the course was the uniqueness and novelty of the instruction strategy and the contextualised format of the questions which they investigated.

I really enjoyed searching for the knowledge when I was searching for my presentation. It was quite interesting. (Student 103)

I was doing the one which is interested me, biocompatibility, so a lot of reading and researching like hip surgeries which was really interesting, so I think they had a really good range of topics we could research, it was really interesting. (Student 71)

I have enjoyed that course a lot more than other courses. (Student 97)

I thought the chemistry was really interesting, it was quite relevant to everyday life. (Student 26)

Furthermore, five of the students found that the Macromolecules course had increased their interest even more.

I have always been interested in chemistry, I would say when I was researching, you read one article and you carry on to another one, it sends you to another, and it grows and grows, and it did make me realise how vast the chemistry is, that is definitely something positive for me, it increased my interest even more. (Student 141)

I really liked it in a sense that I picked a topic that I was interested in and made the research, I went and read about it and I was even more interested in at the end. (Student 8)

The Macromolecules course was seen as a great opportunity by a few students to practise their ability to communicate with an audience whose chemistry knowledge is relatively small. In the Macromolecules course, students were asked to create products which would be understandable by an A-level chemistry student. Some students found connections between the Macromolecules courses and real-life chemists' practices. They claimed that they would need to use this ability to communicate, which would be part of their everyday life practice as a chemist in the future.

You could say so much on your interest topic in chemistry but then people could not understand it always, so to make science understandable to people it was a challenge, but I think it was good in a way because, if you are publishing things later on in your life, you have to make yourself understandable to the people. (Student 71)

If you do science, you have to sort of publish or present and explain it. When I was working in a plastics factory, what I have realised is that whatever you do you have to go and talk to people, you have to be able to explain your research at least to the people who have been funding you. You have to explain it on a far more basic level than actually it is. You have to be able to explain it so they are willing to support it. This course was a great practice. (Student 97)

Finally, during the interviews, two students claimed that it would have been more effective for them if all the courses in the Department of Chemistry had been taught using independent learning strategies. Their main argument was that they remembered much more from the Macromolecules course compared with other lectures, and that they also enjoyed it more.

At the personal level, I would definitely prefer this. In chemistry, every course could have been taught like that, it is not dependent on people's opinion. Anyone who sort of reads the book enough, you don't need to be a doctor of chemistry, you can learn it. It is not like philosophizing issues under discussion, I think for the first-year chemistry courses that I have taken, all could have been taught in this style of teaching. (Student 148)

I literally would prefer to have courses like that, rather than traditional lectures. (Student 97)

7.4.6 Representativeness

The participants were asked to indicate whether their comments represented the overall views of their classmates in order to have an estimation of the representativeness of the interviewees' ideas. As Figure 7.5 shows, the majority of the participants (75%) replied that their ideas were representative of the entire cohort of students, whilst a few of them (17%) said that they had not talked about those issues with their friends so they did not know how representative their ideas were. Finally, 8% of the respondents said that their views were probably personal and did not represent the overall ideas of the other students.

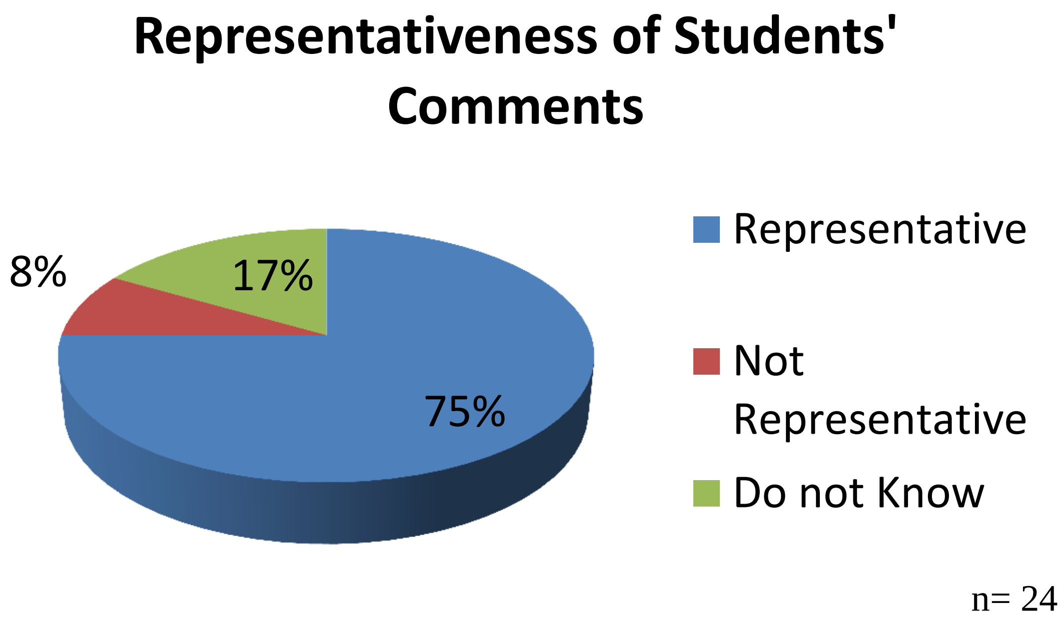


Figure 7.5: Representativeness of Interviewees' Comments

The majority of students, therefore, were confident that their comments were representative.

> *I have that sense that lots of the things that I said are representative. (Student 26)*

> *I have heard quite a lot of people saying the same things. (Student 141)*

> *Probably those are general views. (Student 103)*

On the other hand, there were six students who were not sure whether their ideas were shared by their classmates, and two who claimed that their ideas were only at the personal level.

I think some of them should be same but I am not entirely sure. (Student 14)

I believe those are quite personal views really, I didn't speak to people about this course but I feel they are not shared by all. (Student 97)

7.5 Summary

As the 167 responses to the questionnaire reveal, the features of the Macromolecules course were seen by a small number of students as particularly enjoyable to study and/or as particularly contributing to their knowledge and understanding of chemistry. As the interviews with the 24 students reveal, the arguments for their appreciation of the course included that it helped them to develop a variety of skills, that it gave them a sense of superiority and a sense of discovery, and that they had learned better during the Macromolecules course. On the other hand, it required too much time and effort, there was a lack of interaction with lecturers and other students, it did not involve truly authentic discovery, it was hard to find the 'needed-to-be-learned' material, and it encompassed technology which brought many problems were the main themes which emerged from the students' arguments for their disapproval of the course.

Every student interviewed thought that s/he had developed some useful skills during the Macromolecules course and only two students though that the skills which they had developed were not chemistry-specific skills. There were mixed ideas about the course's contribution to their understanding of education at tertiary level and to their interest in chemistry. The majority of them thought that the course was the first step towards independent learning. They thought that it was a good change from the monotony in their courses and was a required step to take in higher education, but it was not enough to make them become independent learners. They claimed that they needed a gradual decrease in the amount of their dependence on their lecturers before they could become effective independent learners.

The majority of the respondents claimed that they had already been interested in chemistry, so the course did not seem to have any particular impact on their interest in chemistry. However, five students claimed that the course had increased their interest in chemistry even more. Finally, sixteen students said that their views were representative of the entire cohort, two students said their comments were their personal opinions and were not representative, and six students could not make judgements about the representativeness of their arguments.

To sum up, whilst most of the students could give an example of a moment when they were very motivated and interested in the subject during the Macromolecules course, most could also give an example of a lecturer who is motivating and interesting. The results of this research study show that the independent learning strategy applied in the Macromolecules course has its own advantages and disadvantages for the students compared to when students are learning directly from a lecturer, in lecture-based instruction. The findings of this study are in line with those of previous comprehensive reviews of the topic (Bernard *et al*., 2004; Sitzman, Kraiger, Stewart & Wisher, 2006) and expand them by presenting a more detailed and personal picture of students' view of the independent learning approach.

Chapter 8: Conclusions and the Critique of the Study

Introduction

In this final chapter, two main sections are presented. First, the findings of the research study will be placed in the context of the literature reviewed in Chapter 2, the concluding sections of the three preceding chapters will be drawn together, and the possible answers to the research questions laid out in Chapter 1 will be discussed. After this, the approach used in this research study will be discussed critically and possible improvements and suggestions for further research opportunities will be presented.

8.1 Answers to the Research Questions

In Chapter 1, there were three questions set out which this research study would address and attempt to answer:

1) What level of knowledge, understanding and intellectual attributes do beginning undergraduate chemistry students have in relation to the Macromolecules course's content?
2) How are students' levels of knowledge, understanding and intellectual attributes influenced by the independent learning approach?
3) What are the students' views and experiences of the independent learning?

In this section, the findings of the results chapters and the review of the literature in Chapter 2 will be used in order to see how far the research questions have been answered.

8.1.1. Profile of Beginning First-Year Chemistry Undergraduates

The first research question was aimed at establishing a baseline for measuring what levels of knowledge, understanding and intellectual attributes beginning undergraduate chemistry students have in relation to the Macromolecules course's content.

First, in the literature review, in section 2.8 in Chapter 2, it was suggested that some beginning first-year chemistry undergraduates may not have a clear understanding of some ideas which are central to polymer chemistry, such as recycling, intermolecular bonding, polarity and structure-property relationships. They might not, for example, detect intermolecular bonds or interpret their impact on polymers' chemical and physical properties, they might confuse recycling with reuse, or they might misuse chemical vocabulary. In Chapter 5, the findings of the pre-intervention investigation were presented. These findings support and extend the evidence from the literature and present other misunderstandings of beginning undergraduate chemistry students in polymer chemistry-related ideas. In the next section, these will be summarised again in order to establish a baseline before discussing the ways in which student learning was influenced by the independent learning approach used in the Macromolecules course.

8.1.1.1 Students' Knowledge of the Content in the Macromolecules Course

The *Recycling, PIC, Functional Groups* and *Kevlar's Strength* questions were devised to address students' knowledge.

The responses to the *Recycling* question suggest that about a third of A-level educated students can give sufficient valid reasons for the importance of the recycling process; this figure is higher than younger-aged students' responses reported in earlier studies (Daniel, Stanisstreet & Boyes, 2004; Kılınç, Stanisstreet & Boyes, 2008; Kortland, 1992). Although beginning undergraduate students' knowledge about the recycling process seemed higher than earlier-aged students, the 34% of expected answers was less than the desired level before the Macromolecules course and the responses revealed that some of the students' had some misunderstandings about the recycling process. Two aspects of the beginning undergraduate-level chemistry students' ideas about the recycling process are worth discussing here. First, some students thought that all plastics are made entirely of crude oil or that all plastics can be recycled; second, some students thought that re-use and recycling are two words describing the same phenomenon and can be used interchangeably. One possible reason for these misunderstandings could be the everyday use of the word ‘recycling’. It has been shown in the literature that every student has a rich accumulation of interrelated ideas that constitute a personal system of common-sense beliefs about words used in everyday life, and that these ideas can differ quite widely from the scientific use of the word (Champagne *et al.*, 1980). The everyday use of the words ‘recycling’ and ‘reuse’ might lead to some of these misunderstandings.

For the *PIC* and *Functional Groups* questions, there was no response with a sign of misunderstanding given by the students before the Macromolecules course. More than half of the responses generated by these two questions were coded as an incomplete response with no sign of misunderstanding. The students struggled to generate full answers for these two questions and their knowledge seemed to have gaps. The *Functional Groups* question revealed that some of the functional groups such as alcohols, aldehydes or ketones were very familiar to the students, but that the phosphonic acid groups or ester links were not very familiar. The students were more successful at detecting functional groups but they were not as successful at naming those functional groups. Some students thought that carboxylic acid groups were alcohols since they have a hydroxyl group (–OH) and that phosphorous as an element itself was the functional group instead of the phosponic acid group in the polymer.

For *Kevlar’s Strength*, almost a third of the students, 31.7%, were able to give a fully correct answer to this question with no sign of misunderstanding. The most significant problem which some students faced on this question was in understanding the main differences between the chemical activeness and physical strength of polymers. This study has shown that some of the respondents believed that physical strength and chemical activeness refer to the same idea in chemistry. They tended to give reasons which increase the chemical stability and strength of polymers in order to explain physical strength. There appears to be a fundamental problem in students’ understanding of these two different ideas.

8.1.1.2 Students' Understanding of the Ideas from the Content of the Macromolecules Course

The *Branching, Biodegradability, Chelate, Polarity, Isomerisation, Mechanical Strength, Fashion* and *Contact Lenses* questions were devised to address students' understanding.

The findings of this research study indicate that about 60% of the beginning undergraduate chemistry students recognised the branched structures of PE polymers and the impact of branching on the properties of these polymers, a figure which compares favourably with earlier research studies on polymer chemistry teaching (Wagener & Ford, 1984). However, there were still some students who gave responses with a sign of misunderstanding; for instance, some students thought that more side chains meant more intermolecular bonding. This finding can be related to a general intuitive rule (Stavy & Tirosh, 1996) that 'the more of A (the salient quantity), the more of B (the quality in question)'. Those students gave indications that they believed that molecules with more side chains have stronger molecular forces, but they ignored the steric impact of side chains in polymers; these side chains prevent polymers from getting close to each other, and so they cannot form strong intermolecular bonds.

A third of the students did not have any idea about biodegradability and biocompatibility. Some thought that biocompatibility refers to the bonding of molecules to the human body, but biocompatible materials do not need to be bonded to the human body, and the majority of biocompatible molecules do not bond to other chemical structures in the body. In contrast, the students' understanding of biodegradability was relatively better than that of biocompatibility.

The *Chelate* question produced the fewest correct responses in the whole questionnaire. There were only six (7.3%) expected answers to this question and only five (6.1%) students were able to give a partially correct answer. Even though coordinate covalent bonds are introduced to students during their A-level chemistry courses, the respondents still seemed not to comprehend the idea properly. Moreover, the students were not careful enough when they were presenting chemical structures in their answers to this question and their drawings had many chemical and logical mistakes: there were several examples of oxygen atoms that had more than two bonds, carbon atoms with more than four bonds, open-ended bonds and so on. This might be an indication of the argument that some students just memorised the molecular structures rather than completely understanding them.

Again, approximately a third of the beginning undergraduate chemistry students' showed a complete understanding of the idea of polarity in the context of polymer chemistry. One misunderstanding which emerged from this research study about the idea of polarity was that some students believed that the C-H bond was a polar bond as carbon and hydrogen are different atoms, so they thought that isoprene was a polar polymer. This shows that these students did not think about the electronegativity values of atoms and the possible equality of those values, or the geometric structure of the molecules, and basically thought that if there are different types of atoms in a molecule, it is a polar molecule.

Two major misunderstandings of beginning undergraduate chemistry students' about isomerisation were revealed during the study. First, some students thought that cis- and trans- isomers can have a different number of atoms in the polymer or different numbers of double bonds as if they are made from different polymers. Second, some students did not consider chemical interactions or electromagnetic interactions such as repulsion or attraction, but assumed that atoms do not have electrostatic interactions and judged the physical features of isomers depending on this wrong assumption. The first misunderstanding also emerged in previous research studies (Schmidt, 1992) however, the second has not been observed in the context of polymer chemistry before. In terms of the idea of hydrogen bonding, the findings of this study reveal that the students' understanding of hydrogen bonding was quite high, at 35%. This proportion represents a significant improvement on the 21% of beginning A-level students' understanding of hydrogen bonds reported by Barker (1994). The common use of the hydrogen bonding idea in other major courses in chemistry including organic chemistry courses might be a reason for students' success at understanding this idea.

Most of the respondents gave simplistic responses to the *Fashions* question, basically stating that one material was waterproof and the other was not without giving any explanations. About 16% suggested that what makes a polymer waterproof and breathable is that there must be tiny holes too small for water molecules to pass through but big enough for steam molecules to pass through; however, only a very small percentage of these students supported their argument with their chemistry knowledge. Students' attempts to answer the *Fashion* question revealed some basic misunderstandings, such as that steam has a different chemical structure from water.

In the *Contact Lenses* question, the responses showed similarities to those to the *Fashion* question. The majority (56%) of the students failed to show their understanding of molecular structures' physical features relationship in the context of the contact lenses question. As the understanding was defined as an ability to apply knowledge in different contexts (*see* Section 1.3.2) in this research study, it can be claimed that in general students' understanding of the ideas investigated was low. This finding fits the literature that refers to students' low level of ability to transfer their knowledge to different contexts (Duit & Treagust, 2003; Georghiades, 2000).

8.1.1.3 Students' Scientific Reasoning

The *Combustion* and *Wettability* questions were devised to address students' scientific reasoning.

The responses to the *Combustion* reaction question showed that the majority (58%) of the students had naïve, everyday-life explanations for the combustion phenomenon, rather than scientific explanations. This finding is similar to those of previous studies into the high percentage of students who continue to have naïve ideas to describe everyday-life phenomena even after they have studied similar phenomena in science classes (Champagne *et al*., 1980; Gilbert & Osborne, 1980). The majority of the respondents failed to show their chemistry knowledge when they were asked to explain the combustion of polymers. Moreover, the responses showed that some students still had misunderstandings which are established in the literature as children's ideas in science (Driver, 1985). The misunderstanding that 'burning always makes substances weigh less' which was detected in the responses in this current study is a common misunderstanding in the literature, particularly in research studies among lower age groups. This finding may be a suggestive argument to support the robustness of misunderstandings.

The *Wettability* question showed similar findings, since again the majority (54%) of the students were not able to give scientific explanations when they were asked to explain an everyday-life phenomenon (wetting). Although there was no specific misunderstanding of chemical ideas revealed by this question, the main reason for this result might be the low response rate. These two questions were intended to monitor the impact of the Macromolecules course on the students' way of interpreting this natural phenomenon which will then be used as a means to judge their scientific reasoning.

8.1.1.4 Students' Self-assessment Ability

The *Calculation* question was devised to address students' self-assessment ability.

In education, independent learning and autonomy have been associated with a variety of ideas including independence, motivation, taking responsibility, reflection, goal setting, time management, self-assessment, metacognition, self-awareness and self-direction (Garrison, 2003; Hurd, Beaven & Ortega, 2001; Peters, 1998; White, 2003). Self-assessment is a metacognitive process in which learners revisit their actions and measure their intellectual gains. Responses to the *Calculation* question showed that about 10% of the students' could successfully apply self-assessment to their learning. This was much lower than the expected proportion for self-regulated learners. About 40% of the students did not realise their mistake in their calculations and attempted to explain their wrong results instead of revisiting their calculations. Previous studies have indicated high levels of metacognitive abilities among higher education students. However, learners are usually able to exhibit their metacognitive abilities but are not able to show their performance at them (Pressley, Borkwski & Schneider, 1989). This current study shows that the majority of the beginning undergraduate chemistry students failed to show self-assessment ability. One possible reason for this is that much regulation of the cognitive processes is developed without any conscious reflection, so they are highly automatic and not conscious actions. Hence, students seem to know what they are supposed to do for self-assessment but they are not able to exhibit this in their performance.

8.1.1.5 Students' Ability to Generate Creative Solutions

One of the broadly agreed reasons for the low popularity of chemistry courses, possibly science courses in general, is the negative attitude which students have towards science subjects. The assumption that the structure is dogmatic and the lack of creativity are two possible arguments put forward by students who have negative attitudes towards science subjects. As discussed in the literature review, one claimed advantage of independent learning strategies is that they stimulate students' active thinking. Active thinking is defined as how students engage with the content itself. So instruction strategies which exemplify this element demonstrate the expectation that students will use logic, think creatively, build on prior knowledge, and/or make deductions. Responses to the *Disposal of Kevlar* question revealed that 22% of the students could exhibit their creative thinking when they were asked to generate a solution to a polymer chemistry-related problem. This low proportion matches the literature which shows students' lack of creative thinking (Kind & Kind, 2007). The vast majority of the beginning undergraduate chemistry students in this current study (60%) were not able to give any answer to this question. This result supports the view that creativity requires a high level of cognitive ability. Creativity was also put at the top of Bloom's hierarchy of actions in the cognitive domain (Bloom *et al.*, 1956).

8.1.1.6 A Summary of the Responses of the Beginning Undergraduate Students to Diagnostic Questions before the Macromolecules Course

Some of the students did not have a well-developed understanding of the ideas of branching, isomerisation, recycling or biocompatibility. In particular, the branching and isomerisation ideas created difficulties for them in understanding the related topics in polymer chemistry. Polarity and intermolecular bonds in polymers were better understood by the students. Some of them had some knowledge gaps about the use of the recycling process and about functional groups of polymers. They confused reuse and recycling, and they struggled to name some common functional groups. Many of them had poorly developed ability to transfer their knowledge to different contexts, to self-assess their actions and to think creatively. They used naïve explanations and everyday-life language instead of using scientific reasoning when they were asked to explain everyday-life phenomena. Some of them showed misunderstandings about ideas which are fundamental for polymer chemistry teaching. Others continued to carry their childhood misunderstandings in chemistry into their undergraduate studies.

Having established the level of knowledge, understanding and intellectual attributes of the beginning undergraduate chemistry students in polymer-related ideas, the next section will present a discussion of how their thinking changed during their experience of independent learning in the Macromolecules course.

8.1.2 Changes Observed after the Macromolecules Course

Having established a baseline, the next objective was to identify the ways in which the students' learning was influenced by the independent learning strategy used in the Macromolecules course. Chapter 6 detailed the changes in the responses of the students to the diagnostic questions after they had completed the Macromolecules course. In this section, the changes will be summarised under the headings used in the previous section.

8.1.2.1 Questions Intended to Measure the Impact of the Macromolecules Course on Students' Knowledge

Fewer students showed insufficient knowledge about the ideas of recycling and functional groups by the end of the Macromolecules course. However, this increase in their knowledge was not statistically significant within the 95% confidence interval. The number of students who gave a response with a sign of misunderstanding decreased after the Macromolecules course, although again this decrease was not statistically significant within the same confidence interval. Some of the students still believed that every plastic is only made of crude oil and they still had confusion about the differences between the reuse and recycling words. Students' difficulties with PICs and functional groups appeared to have changed relatively little and none of these changes was statistically significant. Their knowledge about the functional groups which are common in polymers used *in vivo* was not affected much by the Macromolecules course. Some of them seemed to have learned to identify ester linkage in polymers better, but this did not have any impact on the results.

A very large increase was observed in the proportion of students giving acceptable responses to the question intended to measure their knowledge increase of a topic which was covered in the first part of the Macromolecules course. About 70% of the students knew the chemical structure of the Kevlar polymer and its features correctly after taking the Macromolecules course. There was also a decrease in the number of students' responses with a sign of misunderstanding, although this decrease was not significant at the 95% confidence interval. The students appeared to have learned the difference between the chemical activeness and physical strength of polymers. These findings show that the students' knowledge from the content covered during the first part of the Macromolecules course had increased statistically significantly, whilst their knowledge from the content of the second part of the course, in which they did their individual investigations, did not change statistically significantly.

8.1.2.2 Questions Intended to Measure the Impact of the Macromolecules Course on Students' Understanding of the Ideas

In the responses to the post-intervention questionnaire, there was no significant difference compared with the responses to the pre-intervention questionnaire to the four questions in this investigation group. The students' understanding of branching, coordinate bonding, biocompatibility and polarity appeared not to have changed significantly during the Macromolecules course. There were still students who thought that molecules with more side chains have stronger molecular forces. There was a slight increase in the number of students who could draw coordinate covalent bonds, but this increase was not statistically significant. The students still made similar mistakes (such as carbons having more than four bonds or Ca^{+2} cations giving electron pairs) over fundamental principles of molecular structures in chemistry when they drew the structures of polymers. Although the students' general level of understanding of the polarity idea in polymers was high compared with other ideas investigated, there was no significant increase found after the Macromolecules course. The students' understanding of biocompatibility and biodegradability were not affected by the Macromolecules course. There was also no statistically significant change in the number of misunderstandings about these ideas after the Macromolecules course.

Some improvements were found in the students' understanding of isomerisation and hydrogen bonds. First, after the Macromolecules course, almost three-quarters of them knew that trans- isomers of polymers are usually more inert than cis- isomers of polymers as they have less steric impact. Fewer of the students confused cis- and trans- isomers, although their responses to this question indicated that their misunderstandings were not totally eradicated after the Macromolecules course. Their understanding of chemical interactions as electromagnetic attraction and repulsion appeared to be improved. Fewer students believed that cis- and trans- isomers of the polymers can have different numbers of elements or double-bonds.

The students' understanding of hydrogen bonds in polymers was also improved significantly during the Macromolecules course. The main reason for this result may be the high level of students' understanding of the hydrogen bonds in polymers prior to taking the Macromolecules course. The responses to the *Mechanical Strength* question suggest that the students had learned the correlation between hydrogen bonding and the physical features of the polymers. These data indicate that the Macromolecules course may have successfully led to an increase in the students' understanding if the piece of knowledge is carefully presented to students in written form as hand-outs.

Little change was observed in the level of acceptable responses to the *Fashion* question, and this change was not statistically significant at the 95% confidence interval. Almost 40% of the students persisted with a simplistic response which focused on the intramolecular bonds of PTFE and nylon polymers. These figures suggest that *Fashion* continued to be a difficult question for the students; few referred to the porous structure of the PTFE and even fewer were able to give reasons for the porous structure.

Responses to the *Contact Lenses* question showed similar patterns before and after the Macromolecules course. Almost 50% of the students were not able to give an answer to the question after the Macromolecules course. These findings show that the students' understanding of the content covered during the first part of the Macromolecules course had increased statistically significantly, whilst their understanding of the content covered by students' independent research had not changed statistically significantly.

8.1.2.3 Questions Intended to Measure the Impact of the Macromolecules Course on Students' Scientific Reasoning

Students' thinking about everyday-life phenomena showed a significant improvement in the level of acceptable explanations. Almost 60% of the students correctly explained the combustion of HDPE and LDPE phenomena using scientific terms. Looking at the literature on students' ideas about combustion reactions (Watson *et al.*, 1997), the number of students who were chemical reaction thinkers increased whilst the numbers of transmutation thinkers and modification thinkers decreased during the Macromolecules course. However, signs of well-established misunderstandings found in the responses of the students prior to the Macromolecules course had not been affected significantly. Answers that were quoted in Chapter 6 emerged again in a quite similar pattern.

A similar change was observed in the level of acceptable responses to the *Wettability* question over the two surveys. Almost 65% of the students were able to give a scientific explanation for the wetting of polymers. These scientific explanations may be considered as representing an improvement in the students' scientific reasoning since these questions required students to transfer data generated through the sorts of interactions with or observations from the real world to the model's world. This ability of transfer is one of the four components of scientific reasoning described by Giere (1979).

8.1.2.4 Question Intended to Measure the Impact of the Macromolecules Course on Students' Self-assessment Ability

The responses to the *Calculation* were almost completely unchanged in any category. The number of students who made the same mistakes, reached the same wrong answers and attempted to explain their wrong answers remained almost the same. There was no improvement in their ability of self-assessment before and after the Macromolecules course.

8.1.2.5 Question Intended to Measure the Impact of the Macromolecules Course on Students' Creative Thinking

A very large increase was observed in the proportion of respondents giving acceptable responses to the question probing their creativity. About 70% of the students who completed the Macromolecules course gave acceptable creative solutions for the disposal problem of the Kevlar material. Around one-third suggested reuse, considering the very slow dissolution rate of the polymer, and gave a valid answer, and about 35% of them gave scientifically correct hydrolysis suggestions for the problem. These responses indicate that the Macromolecules course may have contributed to their creative thinking in polymer chemistry-related contexts, although a number of them still found it hard to come up with a solution to the problem.

8.1.2.6 Effects of the Independent Learning Strategy Applied in Macromolecules Course

The summary and discussion above suggest that the independent learning approach applied in the Macromolecules course can lead to an increase in students' knowledge of and understanding about chemical ideas as well as developing some of the students' intellectual attributes. However, none of these mentioned benefits can be achieved just by allowing students enough space and time and asking students to work on their own: independent learning should be constantly promoted by lecturers for students to receive the mentioned benefits. This result is compatible with the comprehensive reviews discussed in the literature review (Bates & Wilson, 2002; DCSF, 2008; DfES, 2006; Gorman, 1998; Williams, 2003) which concluded that students do not become effective independent learners on their own, independent learning should be promoted (and/or taught) by the lecturers for students to learn how to learn. There are a variety of reasons discussed in the literature for the failure of independent learning strategies. The overwhelming majority of the reasons are related to the lack of fundamental components of independent learning (*see* section 2.3.2). The main reason detected in this current study was that the majority of the beginning undergraduate chemistry students appeared to fail to make the required connection with the intended-to-be-taught ideas of the investigated topic and focused instead on the extraneous context. Moreover, students gather information usually from secondary and tertiary sources which may lead to a variety of misunderstandings. This result reveals that success in independent learning approaches for improving students' knowledge of and understanding about chemical ideas requires very careful preparation and presentation of the content to students. Only allowing students time and space for their own independent investigation did not have any positive impact on students' knowledge and understanding.

As was discussed in the literature review, one of the main conclusions drawn from the literature review was that the vast majority of the literature that show the mentioned benefits of independent learning are from complex teaching approaches which makes it hard to attribute all these mentioned benefits to independent learning itself. In this current research study, the teaching approach investigated employs only independent learning. Hence, the presented benefits on the instruction strategy can be easily and confidently attributed to independent learning itself.

In terms of intellectual attributes, a moderate improvement was found in the students' scientific reasoning after the implementation of the independent learning approach. This result supports the previous findings on the topic (Kuhn & Dean, 2005). As was noted in the literature review, one of the fundamental goals of science education is to improve students' scientific reasoning. Assimilating scientific information requires some understanding of what science is all about and some special abilities for evaluating the information received (Giere, 1979). Especially considering the exceptional increase in scientific information in our lives over recent years, this ability of interpreting scientific information is vitally important for both the professional and the personal lives of people. The ability to understand scientific information can be matter of life and death for students. A specific way of measuring students' scientific reasoning ability in this current study is their ability to understand and explain everyday-life phenomena using their chemistry knowledge. This ability is related to the component of data generated through the sorts of interactions with the real world from Giere's (1979) model of scientific reasoning. The independent learning strategy appears to have had a positive impact on the students' scientific reasoning ability. Scientific reasoning requires some data generated through the sorts of interactions with the real world assumed in the predictions derived from the model which requires an ability to transfer from real world to model's world appropriately. In questions which aimed to measure scientific reasoning, there was the data generated through the sorts of interactions with the real world such as the students' observations of the combustion of HDPE and LDPE polymers. And predictions derived from the model are the end products of combustion reactions of these polymers such as CO_2 and H_2O. It is argued here that the students who gave the correct answers to these questions had better ability to transfer from real world to model's world and *vice versa*; hence they had better scientific reasoning.

This increase in students' scientific reasoning may be because the approach permitted students to actually practise this component during the course. Learning a new intellectual attribute does not seem to be done simply by reading about it. No-one appears to become a critical thinker for instance, by simply studying how to be critical thinker. It seems necessary to practice and to attempt to be critical thinker. The independent learning approaches seem to give students this opportunity to practise, actually to do scientific reasoning or creative thinking, which in turn might lead to an improvement in these intellectual attributes. As mentioned in the literature review, for novice learners the direct instruction approach may be more effective to improve their scientific reasoning (Chen & Klahr, 1999; Klahr & Nigam, 2004); however the results of this current study show that for the undergraduate chemistry students involved, the independent learning approach might also be an effective way of improving their scientific reasoning since it appears to contribute to their ability to transfer from real world to model's world and *vice versa*. This result supports the findings of Kuhn and Dean (2005).

Similar to scientific reasoning, a significant improvement was observed in the students' creative thinking. Creative thinking is the ability of individuals to use the mind to generate new ideas, new possibilities and new inventions based on originality. By taking the Macromolecules course, the students appeared to have improved their creative thinking ability. The change may in part be explained by the fact that the independent learning approaches allow students to see a variety of explanations, exemplifications, demonstrations and representations of similar ideas by investigating them in different contexts. This abundance of interpretations – even though some might include scientifically wrong information – might lead to an increase in students' creative thinking. For example, some students mentioned during their interviews that they had started their investigation from one point which led to another site which referred them to another one and in this way they started to think differently and to have a sense of which one might be correct. However, it is also apparent that this might cause significant problems in terms of students' misunderstandings of the key ideas.

Almost no change at all was observed in the students' ability to self-assess. One possible reason for this result may be that self-assessment is usually considered as a metacognitive ability rather than a cognitive ability, and changes in metacognitive abilities are very hard to observe. Self-assessment requires regulation of cognition; it is claimed to be highly automated (possibly sub-conscious) and in general students struggle very hard to present their self-assessment ability. Maybe the question failed to evoke any change in the students' ability or they failed to show any possible change. This research study shows that the independent learning approach had no impact on students' self-assessment ability. Although independent learning strategy is associated with improvement in self-assessment (Garrison, 2003; Hurd, Beaven & Ortega, 2001), the independent learning strategy adopted in the Macromolecules course did not lead to an improvement in the students' self-assessment ability.

Finally, the independent learning strategy had no positive significant impact on the students' misunderstandings in any of the questions. Furthermore in one diagnostic question, that on Fashion, the number of responses with a sign of misunderstanding increased significantly after the Macromolecules course. These notions are most likely to have developed because the students used a variety of secondary and tertiary scientific information sources – particularly from the internet – during their personal investigations, and they did not have enough comprehension to separate the notions with a sign of misunderstanding from those with no sign of misunderstanding. This result clearly indicates that independent learning strategies should be handled very carefully and implies that improvement of students' misunderstandings may require teaching approaches in which the content of the course is strictly controlled. This finding is on the same lines as those of other research studies discussed in the literature review (Dalbey & Linn, 1985; Fay & Mayer, 1994; Mayer, 2008; Moreno, 2004; Tuovinen & Sweller, 1999).

So it appears that the independent learning approach promotes increases in knowledge and understanding under certain conditions. If students are asked to carry out their personal investigations on their own by being allowed enough time and space, the approach does not lead to any improvement in their knowledge of or understanding about the target ideas. The independent learning approach may be meritorious in developing some intellectual attributes such as scientific reasoning and creative thinking, but any contribution of it to self-assessment ability was not detected in this research study. The independent learning strategy appears to be an ineffective approach for treating students' misunderstandings and in some cases it might actually lead to an increase in the number of misunderstandings. Next, the third research question will be discussed.

8.1.3 Students' Views and Experiences of the Independent Learning Approach

In the literature review, it was concluded that little research is available about students' and lecturers' views of independent learning. Scholars in the science education domain are currently making great efforts to create life-long learners by applying innovative teaching approaches which aim to promote independent learning in higher education and students' views and experiences of the independent learning approaches need to be investigated to improve both the practice and the theory of independent learning. The final research question of this research study was about revealing students' views and experiences of the independent learning approach applied in the Macromolecules course.

Chapter 3 offered a detailed discussion of the rationale for the change from the traditional instruction strategy to the independent learning approach introduced in this study. In this research study, the third research question investigated students' views and experiences of independent learning in the context of the rationale for applying independent learning approaches. It is hoped that revealing students' views and experiences of the independent learning approach in relation to the reasons behind the preference for using the independent learning approach in university-level chemistry education can contribute to the improvement of similar practices in higher education.

8.1.3.1 A Response to the Changing Student Profile in Higher Education?

In section 3.2.1, it was claimed that there has been a change in the student profile in higher education since all students are now brought up in technology-led environments. They interact and learn from a wide variety of media on their own. This shift in the student profile requires an amendment in teaching strategies. It was concluded that regarding the expected features of a teaching strategy which fulfils the needs of the new student profile in higher education, one of the most appropriate theoretical frameworks is the independent learning approach in higher education. One of the important motivations behind the creation of the teaching approach investigated in this research study was to respond to the changing student profile in higher education and to create a course which responds to students' needs more effectively than the traditional lecturing approaches.

Looking at the findings, a number of themes emerged which can be used as an argument that the teaching approach investigated in this research study can be a positive response to adapting to the change in the student profile in higher education.

1) It can contribute to independent learning. The teaching approach investigated was seen by the majority of the students as a way of developing their independent learning abilities. They believed that those abilities will be very useful for them during their tertiary level education and beyond. However, there was no specific example of independent learning abilities which were mentioned by the students.
2) It helps learners to know what many people do not know and gives a sense of superiority. The students thought of the independent learning approach as an opportunity to study when they want to study, to find out about a topic that they are personally interested in, and to learn about the issues that they believe they will face again in the future.

3) It gives the feeling of being a researcher and the sense of discovery. The students seemed to enjoy the feeling of being a researcher and managing their own investigation during the independent learning approach. Some students claimed that they had discovered a great deal of knowledge on their own which had broadened their view of chemistry.

4) It gives students the opportunity to work at their own pace and in their own time, which might lead them to a better understanding of the topic.

In contrast, other themes emerged which can be used as an argument that independent learning approaches are not completely appropriate for the changed student profile in higher education.

1) It requires too much time and effort. The majority of the students argued that this type of instruction strategy is heavily demanding of time and effort compared with more traditionally instructed lectures.

2) It does not involve authentic discovery. Some students related the authenticity of their investigation to the discovery of a piece of information by humankind in general rather than the discovery of a piece of information by themselves. So they did not find the instruction strategy appropriate for 'authentic discovery' settings.

3) It lacks interaction with other students and lecturers. It appears that independent learning approaches require a sense of a gradual increase in student autonomy, since the current student profile seemed to lose interest in learning when faced with a sharp reduction in the amount of interaction with their lecturers.

4) It might increase the extraneous cognitive load as students may find it difficult to interact with the intended-to-be-taught ideas in independent learning approaches. Increased extraneous cognitive load might have detrimental impacts on learning.

5) It involves technology which often creates many problems in use.

In section 3.2.1, it was concluded that the traditional teaching approaches, such as lecturing, are evidently not enough to respond to the needs of the new generation of students who have grown up with digital and cyber technologies, and that new pedagogical approaches need to be developed and applied, especially in tertiary-level education where students have the most freedom and courage to express their needs. One possible instruction approach suggested in the literature which fits better with the current student profile in higher education is argued to be the independent learning approach. It might be concluded from this research study that there might be some relative advantages of the independent learning approach over more traditional instruction approaches. For instance, it might contribute to individual learning 'skills' which are highly appreciated by students, it might create a sense of discovery and superiority in some students, and it might allow students to work at their own pace which might lead to 'deeper learning' in some students' perception.

Furthermore, there are other indications that this type of instruction strategy does not best suit the current higher education student profile in some ways and these therefore need to be improved.

The first thing that should be kept in mind is that independent learning approaches were found too time- and effort-consuming by the beginning undergraduate chemistry students who participated in this study. This load could be decreased with a reduction in the content of the course. It appears from this research study that if the independent learning approach is to be applied for a course which was previously taught in traditional lecturing style, amendments either in the amount of the content or to the time expected to be spent should be made. To cover the same amount of content in the same amount of time as spent in more traditional approaches does not appear to be possible in independent learning approaches.

Second, students' perception of 'authentic' discovery may be different from what lecturers have in mind. In this research study, the students described authentic discovery as the invention of new knowledge or methods in chemistry. They thought that looking for a piece of information which has already been found is not authentic discovery and that it is time-consuming. So if an independent learning approach is applied in inquiry settings, students' perception of what is authentic discovery should be taken into account and the inquiry should be set accordingly in order to increase the effectiveness of the instruction.

Third, the first-year undergraduate chemistry students still appeared to be quite lecturer-dependent in their learning. Many of them thought that the independent learning approach lacked interaction between students and lecturers which in turn had a detrimental impact on their interest in the subject. One possible suggestion to address this might be the gradual decrease of this interaction as the sudden absence of the social interaction was perceived by the students to have a detrimental impact on their interest.

Fourth, in independent learning settings, students might have problems in making contact with the intended-to-be-taught ideas. They might get lost in the context of their investigations. Presentation of the learning objectives and aims appeared to be not enough for the students. One possible suggestion to address this might be that students should be instructed in different methods until their instructors have a sense that their students are sure about what they are expected to learn. Students can then be led to independent learning settings in which they are much more autonomous.

Finally, issues related to technology should be controlled again and again until it is certain that students will go through the process smoothly. There could be introductory sessions in which students go through all the technological materials which they will use during the course, because the potential technological problems which students might encounter seem to be one of the most common issues that put them off the independent learning approaches.

8.1.3.2 A Response to Changing Expectations from Modern Chemists?

In section 3.2.2., it was claimed that in a broader sense chemistry can be seen as a quest for revealing the identity of substances, understanding the diversity in the material and biological world, explaining similarities and differences, transforming nature, and creating things which many might consider impossible. So the way chemists think, build and use models, represent systems and processes, observe appropriately, design experiments, interpret findings and generate explanations and correlate findings with other problems and explanations are the types of knowledge and attributes that undergraduate chemistry students will find useful in their future studies and work. Traditional instruction methods do not correspond sufficiently well to developing those attributes and types of knowledge but independent learning approaches may offer a better solution.

The findings of this research study suggest that independent learning approaches might be helpful for developing students' scientific reasoning and creative thinking abilities. One possible reason for the success of the instruction strategy in developing these intellectual attributes might be the fact that it includes very high student autonomy. As already discussed, the approach permits students to actually practise these abilities during the course. Independent learning approaches seem to give students the opportunity to practise these abilities which in turn might lead to an improvement in those intellectual attributes. To summarise, it may be possible to claim that independent learning approaches might be successful teaching approaches to adapt to changing expectations from modern chemists; hence it might lead to better practice of the expected abilities.

8.1.3.3 Chemical Research-led and Educational Research-led Teaching

In section 3.2.3, it was concluded that using chemistry research and educational research together can empower teaching practice in higher education. One of the motivations behind the Macromolecules course was to create an effective teaching approach which would gain benefits from both educational research and chemistry research. The independent learning approach applied in the Macromolecules course was an attempt to merge chemistry research-led and educational research-led teaching strategies.

The findings of this research study support the findings in the literature that defend the possible respective benefits of chemistry research-led teaching and educational research-led teaching. First, for the vast majority of the students, the most apparent appreciation of the Macromolecules course was that it was a good change from the monotonous lecturing style of instruction in higher education. It became apparent that the students were not accustomed to a course being taught in an independent learning approach, which made their experience more exciting simply because it was unusual and the method is relatively unexplored. It can therefore be concluded that experimentation in teaching approaches is broadly appreciated by students in the higher education context.

Second, there were also clear signs that the independent learning approach applied in the chemistry research-led teaching context was widely appreciated by the students. They claimed that the course helped them to understand the complexity of polymer chemistry and to enjoy the challenge and controversy of different approaches and ethical considerations in chemistry as opposed to the seemingly dogmatic structure of chemistry. These findings are compatible with those of previous findings in the literature (Zamorski, 2002).

8.1.3.4 Attitudes and Interest towards Chemistry and Chemists' Image Problem

Finally, the independent learning approach applied in this study seems to have had relatively little impact on the students' attitudes and interest towards chemistry. All of the students found the teaching approach interesting, but they claimed that the impact of the teaching approach on their attitudes was minimal since they already had positive attitudes to and a high interest in chemistry.

The majority of the students interviewed (14 out of 24) believed that the independent learning approach was an appropriate instruction strategy for teaching chemistry at tertiary level. On the other hand, the rest of them thought that it was inappropriate for teaching chemistry at tertiary level. They frequently used terms such as 'spoon-fed' or 'knowledge transfer' to describe traditionally instructed lectures. Additionally, the independent learning approach was usually associated with self-learning, independent learning 'skills' and learning how to learn.

8.2 Contribution to Knowledge

This study contributes to knowledge in four ways.

First, the results of this study show that the investigated independent learning strategy can have numerous benefits to students including increased knowledge of and understanding about chemical ideas, improved intellectual attributes of scientific reasoning and creativity, and a more satisfying learning experience. Although similar benefits were achieved with other innovative teaching approaches investigated in the literature review (Bell, 2010; Bergmann, Overmyer & Wilie 2012; Finkelstein *et al.*, 2010; Geier *et al*., 2008; Kelly & Finlayson, 2007; Seery, 2012; Tan, 2004), the vast majority of this literature that show the mentioned benefits of independent learning are from complex teaching approaches which makes it hard to attribute all these mentioned benefits to independent learning itself. However, this research study investigates a teaching approach which only involves independent learning techniques; hence all of the revealed benefits in this research study can be attributed to independent learning itself.

Second, the independent learning approach applied in the second part of the Macromolecules course does not seem to contribute to students' knowledge of and understanding about chemical ideas. For the second part of the course, students were asked to carry out an independent investigation into an aspect of polymer chemistry and then present their findings in the format of a written article or short video (*see* Section 3.2.2). It is argued by numerous scholars in the literature (Bates & Wilson, 2002; Black, 2007; Bullock & Muschamp, 2006; Laurillard, 2002; William, 2003), as discussed in detail in chapter 2, that students do not become effective independent learners on their own and independent learning should be promoted (and/or taught) by the lecturers for students to learn how to learn. However, this research study shows that independent student investigations, under the settings applied in the Macromolecules course's second part, may even lead to an increase in the number of students' misunderstandings. Thus, the practice of leaving students to do their own investigations without any support provided should be approached with caution. As Mayer has pointed out, it has been the accepted practice to consider hands-on activities as equivalent to active learning, but active instructional methods do not always lead to active learning, and passive methods do not always lead to passive learning (Mayer, 2009). Chi (2009) explained that although activities requiring hands-on active participation (such as the independent learning approach applied in the Macromolecules course) from learners guarantee a level of engagement greater than passive reception of information, these activities do not guarantee that learners will be engaged to the extent necessary to make sense of the material for themselves. Just because of the fact that people can construct their own understandings in the context of everyday activities, this does not seem to be possible in the context of formal education. The reason might be that the content and context of formal education are extraordinary (Geary, 2008), and require more promotion to reach accurate constructions, understandings and solutions (Sweller, Kirschner & Clark, 2007).

Third, the findings of this research study provide some evidence that students' explanations of scientific phenomena are based on the macrophysical world and they have a limited level of microscopic-level thinking, so lecturers should check that students have acquired the correct scientific meanings of the ideas taught and that they can apply the ideas learned in different situations, whether it is an everyday phenomenon or a theoretical one (Selepe & Bradley, 1997). They should also be checking that students have understood in the way they intended them to (Ribeiro, 1992) in order to eliminate possible misunderstandings of students. Ribeiro, Periera and Maskill (1990) argued that the best way of becoming aware of the shortcomings of one's own knowledge is to rub it up against that of others. Discussions with students might provide a better chance of knowing their shortcomings, and hence remedy students' misunderstandings. The findings of this research study suggest that the independent learning approach applied in the Macromolecules course may be an effective way of increasing students' knowledge of and understanding about chemical ideas; yet it does not seem to diminish the number of students' existing misunderstandings.

Finally, it was pointed out in the literature review that little research is available about students' and lecturers' views of independent learning. This research study gives detailed information about students' views and experiences of the independent learning approach at tertiary-level chemistry teaching. The results of this research study show that the independent learning strategy applied in the Macromolecules course has its own advantages and disadvantages for the students compared to when students are learning directly from a lecturer, in lecture-based instruction. For students, the independent learning approach has some inherited values such as providing the sense of superiority which can lead students to have a more satisfying learning experience. In contrast, it has some other inherited characteristics such as that it is time- and effort-demanding, which are considered repulsive by students. The findings of this study show similarities with those of previous reviews of the students' views of teaching approaches which involve independent learning (Bernard *et al*., 2004; Sitzman *et al*., 2006) and expand them by presenting a more detailed and personal picture of students' views of the independent learning approach. The revealed views and experiences of students should be taken into account to improve the practice of independent learning in tertiary-level chemistry education.

Considering the variety of reasons associated with case studies in general (*see* section 4.1.2 for a detailed discussion) and others specifically related with this research study (*see* section 8.3 below for a critique of the study), it is not easy to generalise any of the findings described above. However, when the concept of 'relatability' was discussed in section 4.1.2 it was concluded that the merit of a case study mainly lies in the extent to which a teacher reading it can relate it to his own teaching rather than in the generalizability of its findings. This research study does not aim to, or claim to, provide the basis for a standard technique to promote independent learning in higher education, which will be deployed by teachers. It shows the benefits and drawbacks of specific teaching strategy which aims to promote independent learning. At most what this thesis can offer is a supplementary resource for teachers at tertiary level to use in situated ways when dealing with the similar contexts they encounter during their practice.

8.3 A Critique of the Study

With hindsight, some aspects of this study could have been improved. There are number of limitations inherent in the research design selected and methodological decisions made that need to be acknowledged and discussed. Possible improvements concern the lack of data relating to the actual learning processes, seeking to measure intellectual attributes by single questions presented in a particular context, the potential of a learning effect when using previously answered questions as a post-test, limits of standardised interviews in exploring participants' ideas in depth and issues related to the generalizability of the findings.

8.3.1 The Lack of Data Relating to the Actual Learning Processes

It was concluded in the literature review that the fundamental components of independent learning can be categorised in two groups; internal components and external components. The internal components are the processing activities that individual learners need to acquire. A review of the literature indicates that there are many processing activities required for independent learning to occur effectively. These usually are divided into three groups: cognitive, metacognitive and affective skills and processing activities.

Cognitive processing activities are those activities which students use to process learning contents and to attain their learning goals. They directly lead to learning results such as knowledge, understanding and skills. Examples are looking for relations among the parts of the subject matter, memorising and rehearsing learning contents, thinking of examples, and selecting main points (Geisler-Brenstein, Schmeck & Hetherington, 1996; Janssen, 1996; Schellings, Van Hout-Wolters & Vermunt, 1996).

Metacognitive activities are directed at regulating the cognitive activities and therefore lead to learning results indirectly. Examples are planning a learning process, monitoring learning progress, and diagnosing the cause of difficulties that arise during learning (Brown, 1987; Volet, 1991). Another aspect is affective processing activities, which are the knowledge, views, conceptions and beliefs people have about learning processes, the functioning of one's own thinking and the variables that influence these processes.

In this research study, no data was collected in relation to specific learning processes. Therefore, whilst diagnostic questions measure students' knowledge, understanding and intellectual attributes; it is impossible to interpret which specific learning processes lead to these learning results. There are two main reasons for not collecting data related to specific learning processes. First, although there are some established methods to measure learning processes, it has been reported in the literature that measuring specific learning processes can be very misleading (Tait & Entwistle, 1996). For instance, Weinstein, Zimmerman and Palmer (1988) developed the Learning and Study Strategies Inventory (LASSI) which contains scales not only in the domains of cognitive processing (for example, 'information processing') and motivation (for example, 'motivation') but also on metacognitive regulation (for example, 'self-testing'); however the findings generated from these established methods have been criticised broadly (Janssen, 1996; Tait & Entwistle, 1996). The main argument behind the criticisms is that learning processes show considerable overlap.

The second reason for not collecting data related to specific learning processes was a practical reason. Giving students another type of measurement in order to investigate specific learning processes would require more time from students and the course leader had only allowed the researcher to spend limited time with the students. In this limited time, the data related to learning results was the priority, rather than the learning processes which directly lead to these learning results discussed in results chapters (Chapters 5 and 6). Although the lack of data relating to the actual learning processes is an important drawback of this research study, it is also an important opportunity to carry out further research.

8.3.2 Seeking to Measure Intellectual Attributes by Single Questions Presented in a Particular Context

As has been emphasized in the literature review, usually intellectual attributes have very complex natures (Keys, 1994; Kuhn *et al*., 1988). Considering their complex nature, scholars who are interested in intellectual attributes usually prefer to limit the scope of their investigations by focusing on specific philosophical and contextual aspects of the topic. Due to the fact that intellectual attributes were measured by single questions presented in a particular context in this research study, the generalization of the findings that emerged from it is somehow unrealistic. However, these findings should be evaluated in their own context. As the data related to the investigated intellectual attributes in the tertiary-level polymer chemistry context is not available in the literature, the context specificity of the findings might also be considered as an advantage.

8.3.3 The Potential of a Learning Effect when Using Previously Answered Questions as a Post-test

For the main data collection, the pre-test/post-test design was employed in this research study. The classical approach of using gain scores in measuring change in pre-test/post-test designs has been criticised for decades (Linn & Slindle, 1977;

Lord, 1956; Cronbach & Furby, 1970). Pre-test and post-test design is fairly common in many research areas. The literature is replete with discussions of the possible effects of the pre-tests on post-test results. Campbell and Stanley (1966) discussed it in their landmark review of experimental design considerations. Bracht and Glass (1968) and Welch and Walberg (1970) presented reviews of the effect of pre-tests on post-test scores. Jaeger (1975) advocated the use of pre-tests for many evaluation and research applications. Welch and Walberg's (1970) summary listed previous results in the usual review format of significance or non-significance. They concluded that the long-term cognitive effects are small or nil, whilst there may be short-term effects. These effects, they suggested, are greater for attitude tests than for cognitive tests. More recent discussions of the topic suggest that although the potential of a learning effect when using the same items as a post-test is a legitimate concern, the reliability of the difference between them should not be thought of as always being low and should not preclude using gain scores in change evaluations (Dimitrov & Rumrill, 2003).

On the other hand, considering the fact that previous research has indicated that using the same questions before and after the instruction may sometimes enhance learning regardless of the success of the instruction (Distad, 1927; Berlyne, 1954, 1966; Samuels, 1969; Welch and Walberg, 1970), the results of this research study should be interpreted under the consideration of a possible learning effect of using previously answered questions as a post-test.

8.3.4 Limits of Standardised Interviews in Exploring Students' Views in Depth

Standardized interviews have been criticized in the literature for various reasons (Oppenhaim, 1992; Cohen, Manion & Morrison, 2004). They allow little flexibility in relation to the interview to accommodate particular individuals and circumstances, and standardized wording of questions may constrain and limit the naturalness and relevance of questions and answers. Hence, it can be argued that using standardised interviews for exploring students' views was a limitation of this research study. There were two main reasons for using standardised interviews as the data collection method in this research study. First, the intention was to collect precisely the same piece of information from each student. Second, because of the researcher's lack of experience in interviewing, a standardised interview was seen as a safer choice compared with deeper semi-standardised interviews in which the interviewer can keep on asking spontaneous questions on pre-decided topics. Although collecting data about students' views with standardised interviews is an important drawback of this research study, it also opens up an important opportunity to carry out further research.

8.3.5 Issues Related to the Generalizability of the Findings

Another important limitation of this research study is related to the generalizability of the findings. Although the research study aims to contribute to both the theory and the practice of independent learning in tertiary-level chemistry education, the findings which emerged from this research study are not particularly generalizable to tertiary-level chemistry education. The main reason behind this low generalizability of the findings is the case-study design. As also has been discussed in the methodology chapter, the case-study design has been criticised for emphasizing the 'instance', the 'particularity' and the 'uniqueness' of the research, hence distinguishing the enterprise as far different from others. This in turn makes the generalisation of the findings almost impossible. In general, the lack of generalizability of the findings appears to be the most significant critique of case-study research. It has been argued by several researchers that generalizability is an expected feature of both the study of samples and the study of cases (Cohen & Manion, 1980; Stenhouse, 1980). Whilst the concept of generalizability is under discussion for case study, it is relevant to consider the suggestion of Bassey (1981) who, in his comprehensive review of research into single events, introduced the concept of the 'relatability' of research. He claimed the relative success of the relatability of research compared with the generalizability of research, especially in the domain of pedagogic research even if not in all educational research. He claimed that educational researchers should eschew the pursuit of generalisations unless their potential usefulness is apparent. It seems that teaching practice could be improved significantly with the help of more relatable research in education. Misleading generalisation attempts may harm teaching practice and should be avoided. It is important to acknowledge here that the generalisability of the findings which emerged from this research study is quite low. Even so, it is hoped that this research study can contribute to the practice of independent learning in tertiary-level chemistry teaching through its high level of relatability'.

8.3.6 Use of Convenience Sampling for Interviews

In this research study, participants for the interviews were not selected at random, but were recruited by invitation. So, it can be claimed that the students who participated in the study were those students who already had an interest in the teaching approach applied in the Macromolecules course. Considering the fact that the students interviewed were not selected randomly, the generalizability of the findings of the interviews can be limited. In a study which compared convenience and random samples, Arnett and Rikli (1981) found that the method of participant recruitment interacted with experimental treatment conditions. In that study, adolescent participants were recruited at random or following a verbal appeal for volunteers for a study involving physical performance. It was found that the verbal encouragement manipulation affected performance. The authors concluded that recruitment strategies may limit the generalizability of results because different recruitment strategies may result in the selection of people with particular characteristics. In this current research study, students were invited for the interviews through an e-mail and this recruitment strategy may have led to the selection of students with a particular interest in the teaching approach of the Macromolecules course.

8.3.7 Other Limitations

Several factors associated with some of the diagnostic questions may have influenced the students' responses. These issues will be discussed in this section.

8.3.7.1 The Diagnostic Structure of Some Questions

Although the majority of the diagnostic questions were prepared in order to reveal possible misunderstandings of students, some questions (*Recycling* and *PIC*) did not seem to be appropriate questions for generating meaningful data to analyse students' misunderstandings. Specifically, the *PIC* and *Recycling* questions did not ask for responses using chemical ideas about the recycling of polymers. It can possibly be argued that anyone without any particular chemistry background could be able to answer these two questions. It could be argued, therefore, that the observed response patterns do not represent particularly the ideas of first-year undergraduate chemistry students. Similarly, questions designed to measure intellectual attributes did not seem to serve their purpose very effectively. The main reason behind this may be the difficulties related to definition and the measurement of the studied intellectual attributes.

8.3.7.2 The Wording of Some Questions

Some questions, specifically *Wettability, Isomerisation* and *Contact lenses*, did not explicitly ask for a response in terms of chemical ideas. Specifically, the *Wetting* question did not ask for responses using ideas about polarity; the *Isomerisation* question did not ask students to explain how cis- and trans- isomers affect the T_g point; and the *Contact lenses* question made no mention of the common parts of the chemical structure of poly methyl methacrylates and poly hydroxyethyl methacrylates. It could be argued that the observed response patterns were influenced by the phrasing of these questions, and that if the relevant terminology had been included, the students would have been better focused on the main intention of the questions.

It is established in the literature that when some students are given chemical terminology, they use it to produce a chemical-sounding answer without understanding the real meaning of these words (Andersson, 1986). So if the *Wetting* question had read 'explain the phenomenon in terms of the polarity of the polymers', some students might have simply responded, 'PVPA polymer is more polar than PCL polymer'. This response would not reveal enough information about the students' level of understanding. By leaving the question more open and not including specific terminology, the students were permitted to respond in the way they considered to be the most appropriate.

Another aspect of the wording of questions which may have affected students' responses is the use of some words which may not be quite familiar to first-year undergraduate chemistry students. For instance, in the *Biodegradability* question the term *in vivo* was used, or in the *Wetting* question the actual word *wettability* might be distracting for students. Although explanations were given for these words, they might have caused some students not to give an answer for these questions. These words might have been avoided.

8.3.7.3 Data Analysis Issues

The data tables showing the students' responses to the questions in Chapters 5 and 6 provide extensive information about the impact of the Macromolecules course on students' learning. An additional analysis could have been included exploring the extent to which individual students' responses occurred across more than one question. Considering the fact that there was some overlaps between questions created with different aims, for example, the *Neoprene*, *Contact Lenses* and *Wettability* questions were all somehow related to the polarity idea, finding common themes in the students' responses to questions in different groups might have helped to identify their difficulties in more detail. Moreover, looking at students' answers for two different questions probing similar ideas could help to increase the accuracy of the detected misunderstandings of students about the chemical ideas.

Even though with the data collected it was entirely possible to carry out such an analysis, it was not carried out since cross-question comparisons are very large and complex, and it was definitely hard to see how far their links should be chased to find useful connections. Moreover, what questions such an analysis would have addressed was not clear during the data analysis process. So it was decided not to carry out extensive cross-question analysis.

8.3.7.4 Lack of Further Measurement of the Impacts

With hindsight, it might have been fruitful to add measurements to observe students' intellectual attribute developments detected in the research study in order to improve the robustness of the findings. This type of measurement, such as an observation of students' behaviours, would have added depth to the characterisation of their development. An examination of students' study habits, for instance, would have provided detailed information about their claimed change in their perception of studying chemistry at tertiary level. However, mainly because of the practical and ethical difficulties involved, it was not possible or practical to carry out observations of this kind.

In conclusion, although some questions could have been better formulated in one respect or another, the majority were clear and unambiguous as was established by the pilot study. All of the questions produced a range of responses and consistent response types over the two surveys. Careful examination of the scripts indicated that most students could answer most of the questions, suggesting that despite the weaknesses discussed above, the questionnaires were indeed valid instruments for data collection. Furthermore, although some further data analysis could have been carried out with the help of further data collection, valid and valuable conclusions can be reached with the data collected and analysed in this research study.

8.4 Concluding Comments

This study has provided some interesting and valuable data about the impact of an innovative teaching approach which aims to promote independent learning in tertiary-level chemistry education. The project has revealed that independent learning approaches can be useful for increasing students' knowledge of and understanding about chemical ideas as well as improving some of their intellectual attributes under certain conditions. Furthermore, independent student investigation applied in the Macromolecules course was found to be ineffective at increasing students' knowledge of and understanding about chemical ideas. In some cases, this technique might even lead to a detrimental impact on undergraduate chemistry students' understanding. Only carefully prepared learning materials used in independent learning approaches might lead to an improvement in students' knowledge of and understanding about chemical ideas. This suggests that the independent learning approach requires meticulous effort and preparation to provide powerful learning experiences for students in educational settings in which the acquisition of knowledge and understanding are put as fundamental aims. It is important to emphasize that, as the results of this research study clearly show, independent learning does not simply involve giving learners more independence. It involves educators thinking clearly about learning outcomes and learning stages and creating enabling environments which lead to these learning outcomes and stages. Independent learning does not only require learners working alone, it also requires more capable others, lecturers, tutors or other peers, guiding learners towards becoming more independent.

If applied appropriately, independent learning strategies can also lead to an improvement in students' intellectual attributes as well as their knowledge and understanding. It is crucially important for students to be improved in intellectual attributes particularly during their tertiary-level education. There are two main reasons for this argument. First, this is the final level of formal education for the vast majority of people and these attributes are very likely to be needed by them in their subsequent lives. Second, as mentioned in the literature, these attributes are usually considered by future employers as vital skills that a modern chemist should have, and for students' future employment which will allow them to practise their science. Students of all chemistry courses would benefit if they were given the opportunity to practise and develop their creative thinking and scientific reasoning abilities. The challenge now for chemical educators is to improve teaching strategies which meet these needs of students without compromising students' knowledge of and understanding about key ideas in the domain. The findings of this research study can contribute to this purpose.

As this research study shows, activities in independent learning approaches, as in all teaching methods, cannot be expected to work perfectly in all conditions, but do provide some benefits along with the disadvantages. We need to learn the lessons of each implementation of innovative teaching approaches, and then use those lessons learned to improve both the practice and the theory. In this way, we can slowly build a body of knowledge of how best to use teaching approaches, and a teaching profession that knows what it is doing and why.

Appendices

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Appendix 2: TOPICS FOR INDEPENDENT INVESTIGATIONS

Appendix 3: MARKSCHEME FOR INDEPENDENT INVESTIGATIONS

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Appendix 7: LECTURER INTERVIEW QUESTIONS

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Appendix 1

INDEPENDENT LEARNING PACKAGE

MACROMOLECULES

Plastic Fantastic???

Year 1

Independent Learning Package

2012

MACROMOLECULES

I. GENERAL INTRODUCTION TO POLYMERS

The Polymer Age

We are living in 'the polymer age' – like in the stone age, iron age and bronze age, one type of material has completely transformed the way we live – polymers. We now know that polymers are giant molecules with molar masses ranging from several thousands to several millions. However, even in the late 1920s this concept was ridiculed. One of the pioneers of polymer chemistry famously received a letter which read:

> *'Dear colleague.....there are no organic molecules with a molecular mass over 5000. Purify your products and they will crystallise and reveal themselves as low molecular weight substances'.*

From this humble beginning polymers have gone on to become the most heavily used compounds in the modern world. It is fair to say they have enabled the lifestyle we currently lead. For example, before polymer coated electrical wires, wires had to be wrapped in paraffin-soaked paper – leading to a high incidence of fires. Before thin, sensitive yet resistant latex condoms, sheep's bladders were used for the same task and washed out after use. Already, 25% of the weight of a car is now made up of polymers – a figure which is only set to increase because polymer-based cars are lighter and therefore more fuel efficient.

Sheep's Bladder
Natural Polymers

Latex
Synthetic Polymer

Flexible, thin
fabrics

Bullet-Proof
Fabrics

One of the fascinating aspects of polymers is that they have a hugely tunable range of physical properties, from adhesives to artificial joints, from thin flexible food wrap and nylon stockings, to bullet proof fabrics, and from highly heat chemical/resistant materials for use in aeronautical/space engineering to easily melted waxes. All of this behaviour is achieved by simple chemical manipulation. The technology of the mobile phone and laptop computer would be impossible without modern polymer science. Furthermore, modern polymer chemists are currently designing next generation nanomaterials with applications in medicine, solar cell technology and the electronics of the future.

Definition of a Polymer

A **polymer** is a large molecule made by linking together repeating units of small units called **monomers**. Poly (many) mer (small unit). The process of linking monomers together is referred to as polymerisation.

YOU do the work. Find the molecular structure of any polymer and sketch & name it below:

Historical Overview of Polymers

The **first synthetic plastic** was celluloid, invented in 1856.

Using the web – ***YOU do the work!***

What natural material did it replace?

Applications:

Hint/Further Question: Why did billiard balls explode?

The **first synthetic fibre** was rayon, developed in France in response to a silk shortage in 1891. The polymer was given its name because it was shiny and appeared to give off rays of light.

The **first synthetic rubber** was made by German chemists in 1917.

YOU do the work? Why do you think synthetic rubber was invented in Germany in 1917?

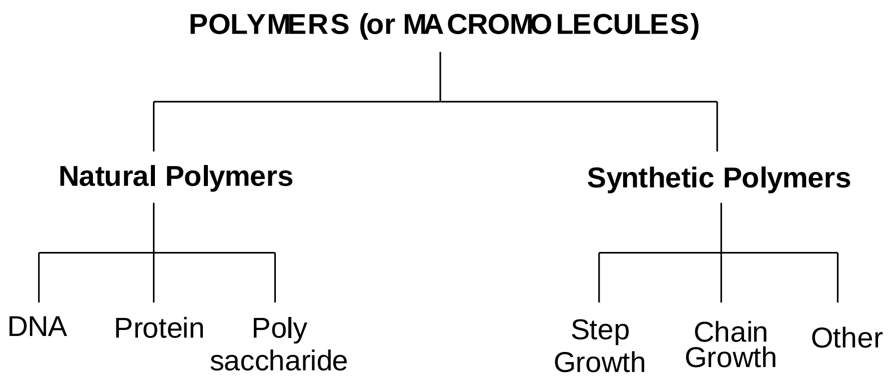
Hermann Staudinger (Nobel Prize 1953) was the first scientist to realise that polymers were made up of continuous chains of *monomers* joined together covalently. As such, he was the pioneer of polymer chemistry. Over the past 100 years, the development of new polymers has been continuous – and as we will see, modern life would not be possible without polymeric materials.

To find out more about Herman Staudinger, and his Nobel Prize winning work, check out:

http://nobelprize.org/nobel_prizes/chemistry/laureates/1953/staudinger-bio.html

Classification of Polymers

Polymers can be divided into *natural* and *synthetic* polymers. This course will focus primarily on synthetic polymers. You will learn more about natural polymers (biopolymers) in the course *Introduction to Biological Chemistry* as well as biological chemistry courses in the second year. Increasingly, in modern polymer science, the boundaries between different types of polymers are becoming blurred – as synthetic chemists use natural building blocks to build synthetic polymers and molecular biologists also use synthetic methods to modify naturally occurring biopolymers.



We need to consider what is meant by chain growth and step growth polymerisation, as these may be terms you have not met before.

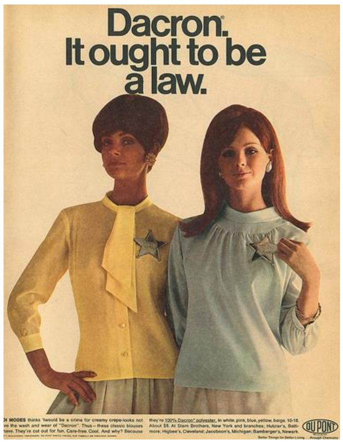
Introducing Chain-Growth Polymerisation (Addition Polymerisation)

Chain-growth polymers, sometimes known as addition polymers, are made by the addition of alkene monomers to the end of a **growing chain**. The end of the chain is reactive because it is either a radical, an anion or a cation. You will notice that the main chain (or backbone) of the polymer is only constructed from the carbon atoms which appear in the alkene group. The mechanism of this reaction will be discussed in more detail in Section 3.

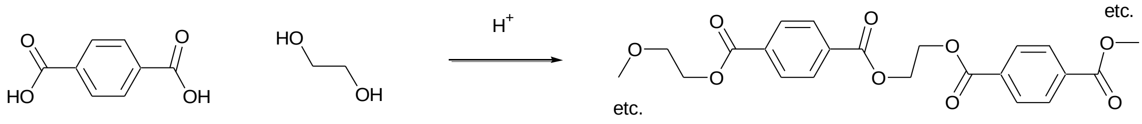
Polystyrene is a good example of a chain-growth polymer.

YOU do the work. Draw a reaction scheme similar to the one above for the conversion of propene into poly(propene) and give an application of polypropene.

Introducing Step-Growth Polymerisation (Condensation Polymerisation)



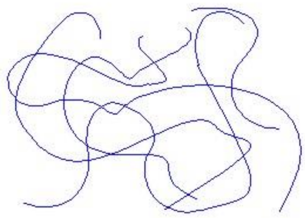
Step-growth polymers, also known as condensation polymers) are made by combining **two reactive functional groups**, while in most cases removing a small molecule (typically water or an alcohol). The reacting molecules have reactive functional groups **at both ends**. Any molecules with appropriate reactive end groups can combine in step-growth polymer formation. For example carboxylic acids can combine with alcohols to give esters. The example shown is known as Dacron^{TM}, which is a good example of a step-growth polymer – and although fashions may have moved on from the picture, this polyester is used, or blended into many wrinkle-resistant fabrics.



YOU do the work. Using Chemistry[3], find the mechanism for *acid catalysed* condensation of a carboxylic acid and an alcohol to give an ester and draw it fully in the space below. You will learn more about this reaction in your course on carbonyl chemistry.

The Statistical Nature of Polymer Chains

In a real polymer sample consisting of many polymer chains, the polymer chains do not all have precisely the same molecular mass. A spread of masses will arise with some polymer chains being longer than average and some being smaller. This is a difference between synthetic and natural polymers – protein macromolecules have precise chain lengths and structures.



The question is therefore – how should the molar mass of a synthetic polymer be quoted? Should the lowest or highest mass be given, or an average – if so which average should be used (mean, median or mode) or perhaps a range of masses could be given?

The easiest method of calculating the mass is to use the **simple mean molecular mass**. This is calculated by working out the total mass of polymer, and then dividing it by the number of polymer chains present (giving the mean mass of each chain). This is referred to as the **number average mass** because the average is taken with respect to the *total number* of polymer chains present in the sample. The number average mass of a polymer is designated as M_n.

For example, if we mix together 100 polymer chains with mass 10000, and 100 chains with mass 20000, then intuitively the number average mass, M_n is 15000.

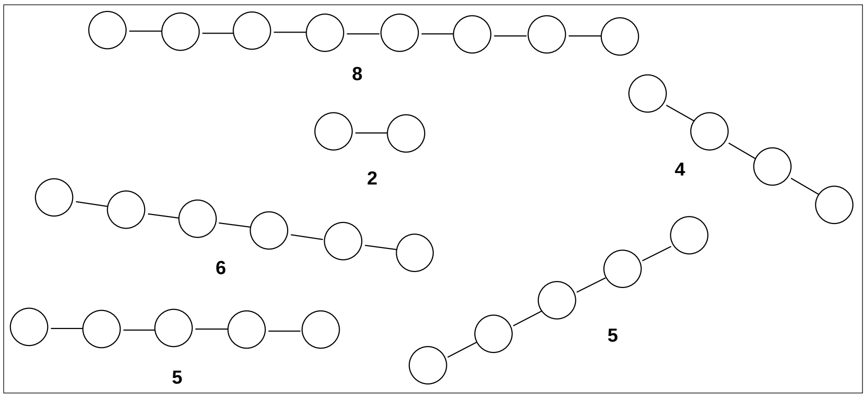
We can express the **number average molecular mass (M_n)** mathematically.

$$M_n = \frac{\Sigma N_i \times M_i}{\Sigma N_i}$$

M_n = number average molar mass
N_i is the number of molecules with an RMM of M_i

In this equation, the sum on the top is equivalent to the *total mass of polymer* whilst that on the bottom is the *total number of polymer chains*.

WORKED EXAMPLE. For the model distribution of polymers shown, calculate the value of M_n.



M_n = (1x8) + (1x6) + (2x5) + (1x4) + (1x2) / (6)

M_n = 30 / 6

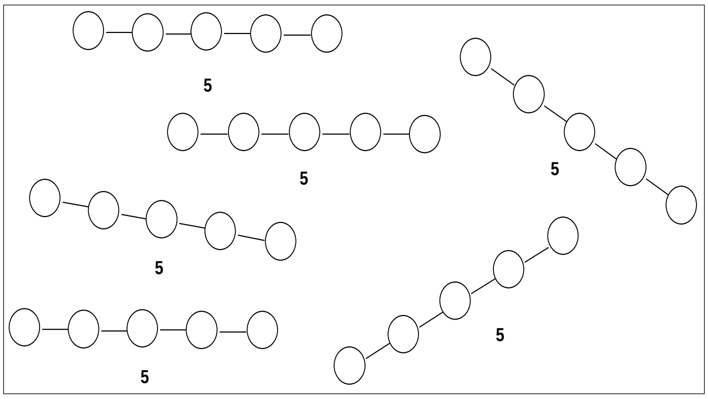
M_n = 5

However, whilst the value of M_n tells us usefully about the mean mass of a polymer chain, it does not provide any information about the **range of different molecular masses** present within the sample. Consider, for example, the sample of polymers:

M_n = (6 x 5) / 6

M_n = 30 / 6

$\boldsymbol{M_n = 5}$



The two distributions on the previous page have exactly the same values of M_n, yet are very different. The first sample is very **disperse** (polymers have differing chain lengths) whilst the second sample is **very well defined** (all the polymers have the same chain lengths). We need a way of mathematically capturing this information. For this reason, we introduce a *second* measure of molecular mass, the so-called, **weight average molecular mass (M_w)**.

The weight average molecular mass is measured with respect to the **total weight of polymer**, and therefore the value on the bottom of the mathematical expression represents the **total weight of polymer**.

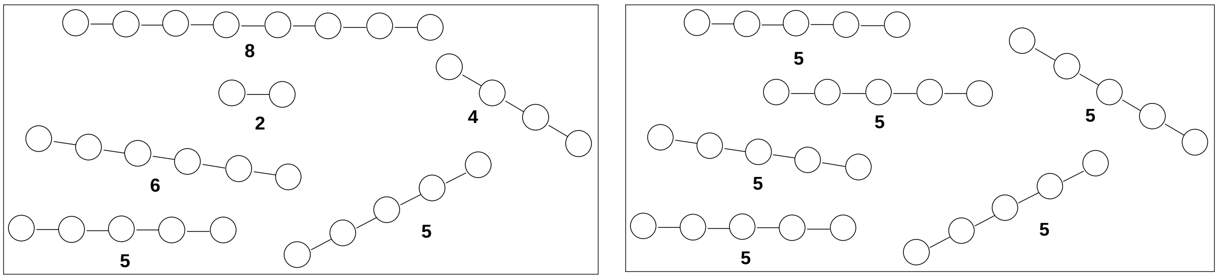
$$M_w = \frac{\Sigma N_i \times M_i \times M_i}{\Sigma N_i \times M_i}$$

M_w = weight average molar mass

N_i is the number of molecules with an RMM of M_i

This is a *weighted average* in which the higher mass polymers count for proportionately more than the lower mass polymers. This may seem a strange thing to do, but we will see later how this can be measured and why it is useful.

If we consider again the two sets of polymers



For the first set:

M_w = (1x8x8) + (1x6x6) + (2x5x5) + (1x4x4) + (1x2x2) / (1x8) + (1x6) + (2x5) + (1x4) + (1x2)

M_w =64 + 36 + 50 + 16 + 4 / 30

= 170 / 30

M_w = 5.67

Whereas for the second set:

M_w = (6x5x5) / (6x5)

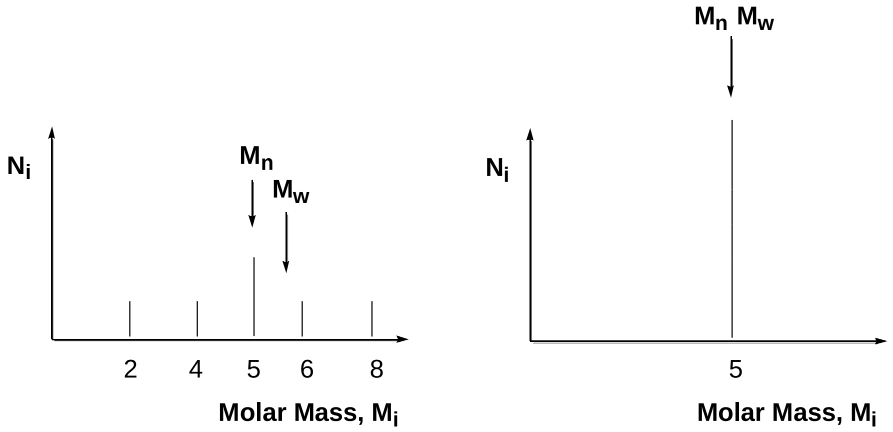
M_w =150 / 30

M_w = 5.00

Because the first set of polymers has more high mass polymers, these skew the distribution and pull the average up – M_w is therefore higher than M_n.

However, for the second set of polymers, because all the chain lengths are exactly the same, M_n and M_w work out to have exactly the same value – there are no high mass polymers to pull up the value of M_w.

We can see this difference most clearly if we plot the polymer distribution graphically, with the mass of the individual polymer chains on the x axis, and the number of polymer chains on the y axis.



This is why calculating both M_n and M_w is useful. Any difference between M_n and M_w effectively represents the broadness of the polymer mass distribution.

In fact we can define a new term, the **polydispersity** of the polymer. The polydispersity index (PDI) represents **how broad the mass distribution of a polymer sample actually is**. You can think of it as being related to the concept of a mathematical standard deviation.

$$\frac{M_w}{M_n} = \textbf{Polydispersity}$$

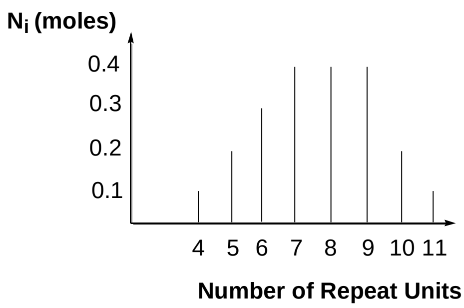
In the examples discussed above, the polydispersity would have been 5.67/5 = 1.13 for the first set of polymers. But for the second polymer, the polydispersity would have been 5.00/5.00 = 1.00.

The higher the value of the polydispersity, the more 'imperfect' the polymer is – i.e., the greater the range of molecular masses.

For a pure sample of a normal organic molecule (i.e. not a polymer), all the molecules have exactly the same molecular weight, and therefore the PDI would be 1.00. In fact, the second polymer sample used in this example can be considered to be a 'perfect polymer' just like any ordinary organic molecule.

In recent years much effort has been spent trying to make polymerisations as well controlled as possible so that a very small spread of polymer chain lengths is generated. By targeting 'perfect' polymers with low polydispersities in this way, the polymer chemist can have much **more precise control of the physical and mechanical properties of the polymer**.

YOU do the work. From the graph below representing polymer masses, calculate the M_n and M_w values and the polydispersity of the sample of polystyrene.



HINT: You will need to work out the mass of a repeat unit in polystyrene. You do NOT need to convert the number of moles of polymer chains into the *actual* number of polymer chains (you can use any units for N_i as the units cancel out in the equations for M_n and M_w).

Space for calculations:

Check Your Answers (M_n = 787.4, M_w = 831.3, Polydispersity = 1.06)

If you have problems with this, or any of the problems on the worksheet, why not go on the forum and chat about it with other students on the course. If you cannot sort things out, the course leader may get involved and help out.

2 ANALYSING POLYMERS

In the examples above, we just assumed that we know exactly how long polymer chains are, and can easily count the number of polymers with each chain length. Clearly we are going to need some effective ways of analysing polymers if this is going to be possible. Only with some good methods of analysis will we be able to accurately measure, M_n, M_w and polydispersity values.

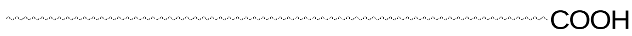
Firstly, we will consider some of the older/historical methods of determining M_n and M_w then we will introduce the modern methods, which are much more powerful and widely used.

Measuring M_n

To measure M_n we need to be able to effectively (i) *count* the total number of polymer chains and (ii) determine their total mass. Dividing the total mass by the total number then yields the M_n value according to the equation on page 10.

End Group Analysis. If the polymer has an end group that can be determined by physical (*e.g.* NMR) or chemical (*e.g.* titration) means, we can effectively count the total number of polymer chains.

WORKED EXAMPLE. Polymer A (0.5 g) is titrated against aqueous NaOH (0.01 M) and requires 17 mL of alkali to be fully neutralised. Hence calculate the M_n value of polymer A.



Polymer **A**

The number of moles of alkali used in the titration is (17/1000) x 0.01 = 0.00017 moles

Each mole of alkali must neutralise a mole of COOH. Therefore:

Moles alkali = Moles COOH = 0.00017

There is one COOH on each polymer chain, therefore:

Moles COOH = Moles Polymer = 0.00017

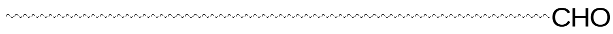
Therefore 0.5 g of polymer corresponds to 0.00017 moles.

M_n = Total Mass of Polymer / Total Number of Polymer Chains (in moles)

= 0.5 / 0.00017

M_n = 2941.2

YOU do the work. In an NMR analysis, the integral for the aldehyde end group (CHO) of polymer B is four times smaller than the integral for a reference compound (benzene, C_6H_6), which is present at a concentration of 1 mM. Given that the NMR sample (volume 0.5 mL) contains 30 mg of polymer B. Calculate the



Polymer B

M_n value of polymer B.

Check Your Answers (M_n = 40,000)

If you have problems with this, why not go on the forum and chat about it with other students on the course. If you cannot sort things out, the course leader may get involved and help out.

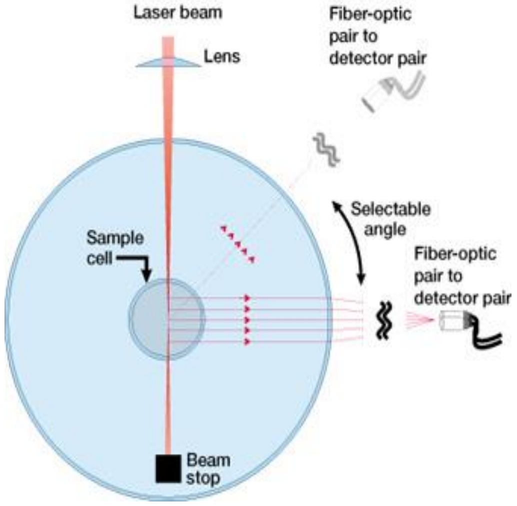
Note that the concentration of end groups on a polymer is low (only one end group on a long polymer chain) – and therefore calculations using this method are only really possible with any degree of accuracy up to polymer masses of around 50000.

Freezing Point Depression, Boiling Point Elevation and Osmotic Pressure In the same way that adding salt can modify (lower) the freezing point of water, and therefore be used to keep the roads free of ice, any additive can modify freezing point/boiling point and osmotic pressure of any given solvent. The magnitude of this effect depends on the *number of particles* which are present. Monitoring these properties is therefore a good way of effectively 'counting' the number of polymer chains in a given sample. You do not need to know how to calculate these properties in detail, however, it should be noted that the effects of polymers on solution properties are very small and sensitive measurements must be made.

Measuring M_w

Some behaviours of a polymer are *biased* by the presence of *heavier polymer chains* – which have a much larger effect on the property being measured than the lighter chains. These methods reflect the **weight average molecular mass** which is also biased in the same way, and therefore these techniques offer a way in which M_w can be directly measured.

Light Scattering. As light passes through a polymer solution, it is scattered by the large molecules – this effect is biased in favour of the largest molecules. By measuring the ratio of scattered to incident light, the solution turbidity can be calculated and hence the value of M_w can be worked out. You do not need to know the mathematical theory behind this technique.



Sedimentation. By measuring the rate at which large polymer particles fall in a solution, the mass average of those particles can be calculated. A centrifuge can be used to make the particles sediment more rapidly. You do not need to know the details of the calculations.

Viscometry. When dissolved, a polymer molecule increases its dimensions and becomes more viscous (think of adding wallpaper paste to water). This effect is once again most dependent on the heaviest polymer chains, and therefore, by measuring the viscosity at different concentrations of polymer, the M_w value can be calculated. Viscosity is often measured by monitoring how long it takes a dilute solution of the polymer to fall a fixed distance (e.g. between marks A and B in an Ubbelohde viscometer) at a fixed temperature under the force of gravity with a capillary tube limiting the flow rate. You do not need to know details of the full calculation. However, you should be aware that this is not an absolute technique because the experiment must been calibrated using known standard samples of polymer and solvent. This can make the technique somewhat time consuming and tedious. In addition, the value found this way is not strictly the true M_w (because of non-ideal non-Newtonian effects) although it is often close.

Global Methods for Characterising Mass Distributions

All of the methods above provide insight into either M_n or M_w, but they do not provide an overall view of the mass distribution. In particular, they do not allow you to work out whether your polymer distribution is ‘normal’ (i.e. bell-shaped curve), asymmetric (distributions which are biased towards having more heavy polymers or more light poymers) or even bimodal (one set of much smaller polymers, one of much larger polymers) – the methods described above will just give simple numerical values. Methods which can provide an overview of the total polymer mass distribution are therefore very useful.

MALDI Mass Spectrometry

Mass spectrometry is perhaps the most powerful way of analysing polymer mass distributions, although it does requires specialist and expensive equipment. The biggest problem is that polymers are very large molecules, and it is therefore difficult to make them 'fly' without providing them with so much energy that thy break apart (fragmentation). In recent years, however, special methods have been developed for gentle ionisation of complex compounds – in particular electrospray mass spectrometry (see mass spectrometry course) and Matrix Assisted Laser Desorption Ionisation – Time of Flight (MALDI-TOF) mass spectrometry. In 2002, the Nobel Prize was awarded for the development of these analytical techniques, specifically because of their importance in analysing biopolymers.

For details of the Nobel prize winners see:

http://nobelprize.org/nobel_prizes/chemistry/laureates/2002/

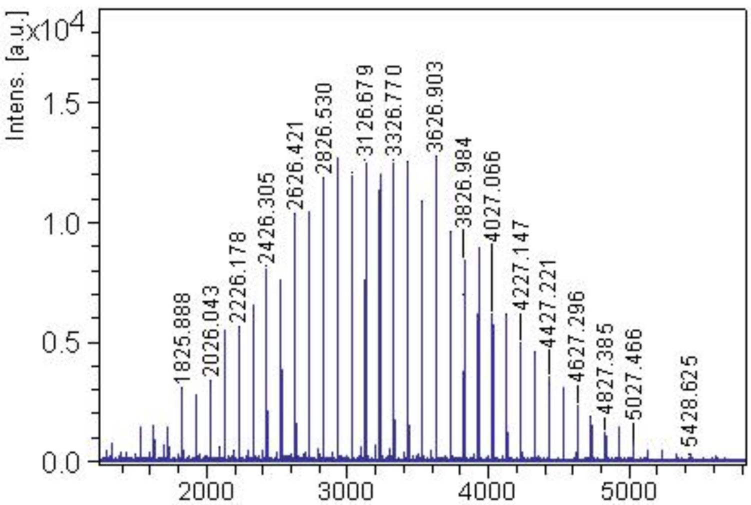
YOU do the work. Which of the three prize winners was responsible for MALDI-TOF?

MALDI-TOF works as follows:

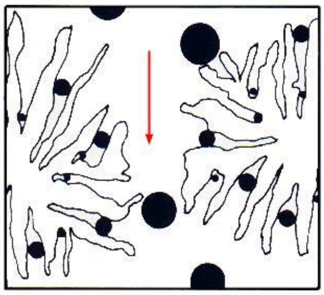
1) Dissolve the polymer in a solvent and add it to an excess of a UV absorbing molecule
2) Evaporate the solvent (this leaves the polymer suspended in a matrix
3) Irradiate with a UV-Laser
4) The matrix is excited and passes the energy to the polymer assisting its desorption and ionisation
5) The polymer flies into the spectrometer
6) The length of time taken for the polymer to hit a detector is measured, and this time of flight reflects the mass of the polymer.

YOU do the work. Sketch a schematic diagram of a MALDI-TOF mass spectrometer.

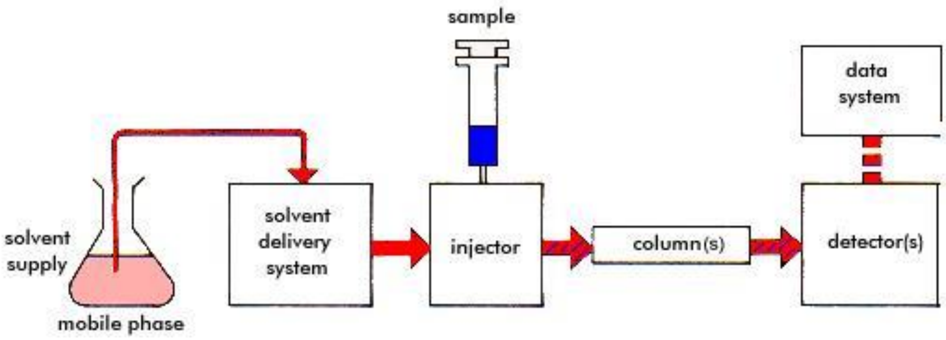
Looking at a MALDI-TOF spectrum we can see a peak for each different polymer chain length. The peaks are separated by a mass which corresponds to a single repeat unit – in this case ca. 100 mass units. The relative number of each polymer chain present in the distribution can be simply read off the y-axis of the graph. In this way, a MALDI-TOF spectrum can be used to calculate both M_n and M_w as well as the polydispersity, using the methods outlined on pages 10-13.



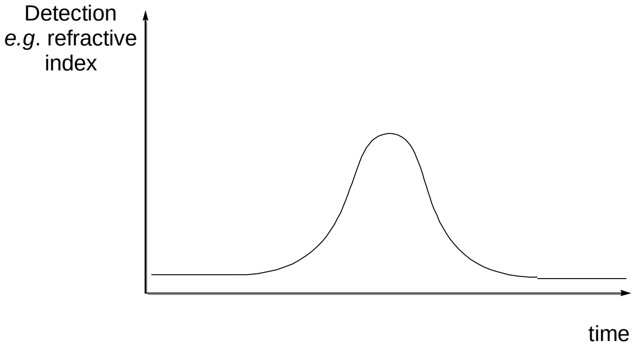
Gel Permeation Chromatography (GPC)



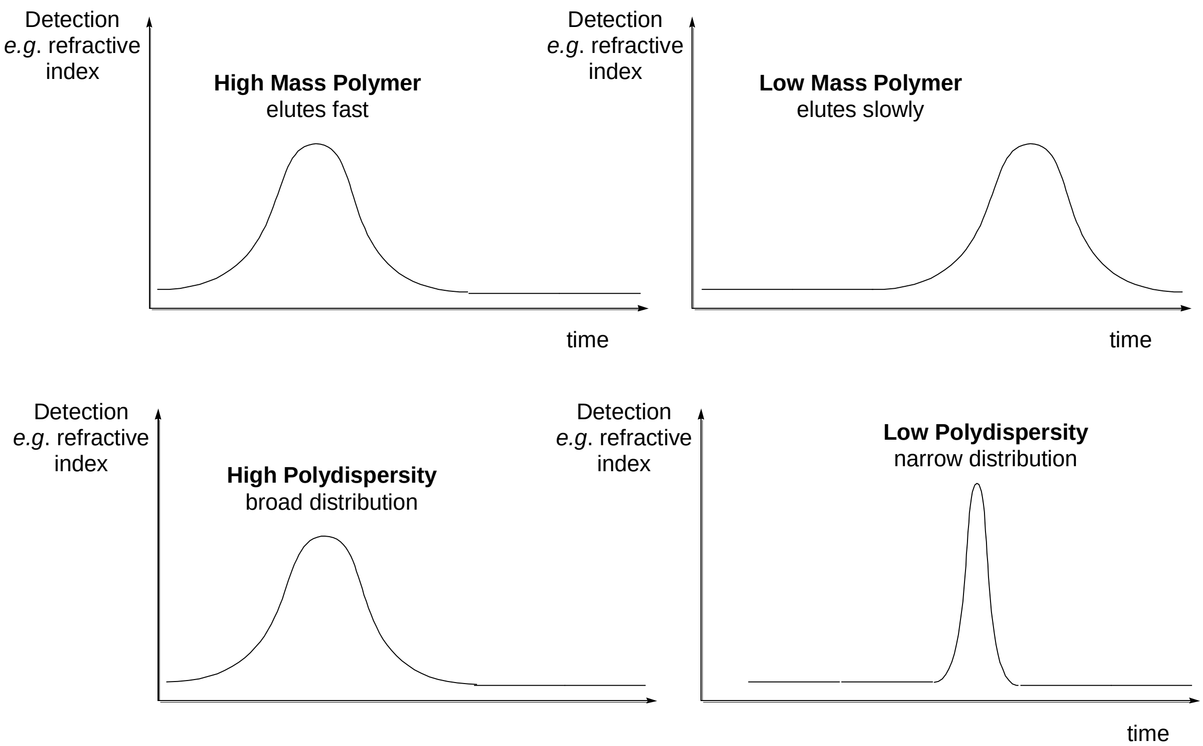
Gel permeation chromatography (GPC), sometimes known as size exclusion chromatography (SEC), offers a quick and relatively cheap way of gaining an insight into a polymer mass distribution. In this type of chromatography, the analytical columns are packed with mechanically stable, highly crosslinked gels, which have a distribution of different pore sizes and can, by means of a sieving action, separate a polymer sample into fractions, dependent on their **molecular size**. The large molecules are excluded from the smaller pore sizes in the gel and pass quickly through the large channels between the gel particles. **The large polymers therefore elute first.** As the size of the polymer chain decreases the molecules can diffuse into the smaller pores in the gel, and they get slowed down. By choosing a series of columns with appropriate pore sizes, separation across a wide mass/size range can be obtained. The eluting polymers can be **detected** by monitoring their UV-vis spectroscopy or the refractive index of the solution.



As can be seen from the typical GPC trace shown below, it is not possible using this technique to see individual peaks for each molecular mass of the polymer separated by just one repeat unit – the technique does not have enough **resolution** to resolve masses which are very close to one another. Typically a 10% difference in mass is required for chromatographic resolution to be obtained – so a broad average peak which represents the overall mass distribution is obtained.



It is possible by simple inspection for some information about a polymer to be obtained just by looking at a GPC trace. The retention time indicates some information about the mass, with smaller retention times indicating higher masses. The breadth of the peak represents the polydispersity (i.e., range of masses). Broad peaks indicate more disperse samples.



YOU do the work.

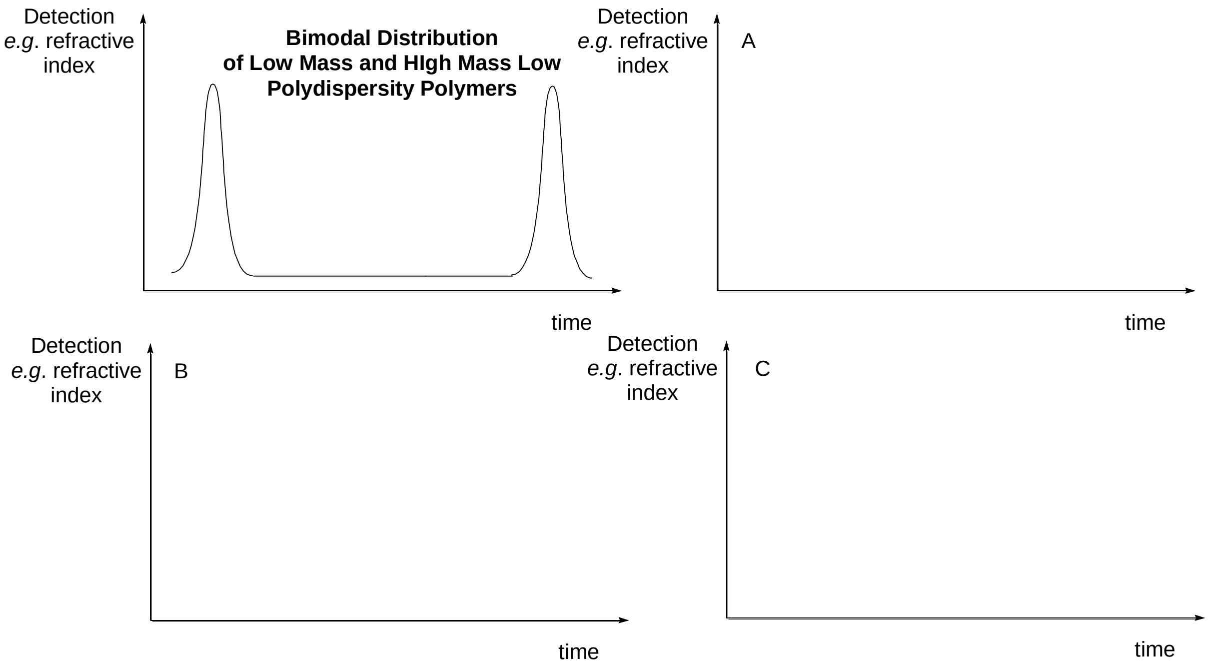
On the empty plots below, have a go at sketching the appropriate mass distributions.

A) A bimodal distribution of low polydispersity polymers with more high mass polymer than low mass polymer;

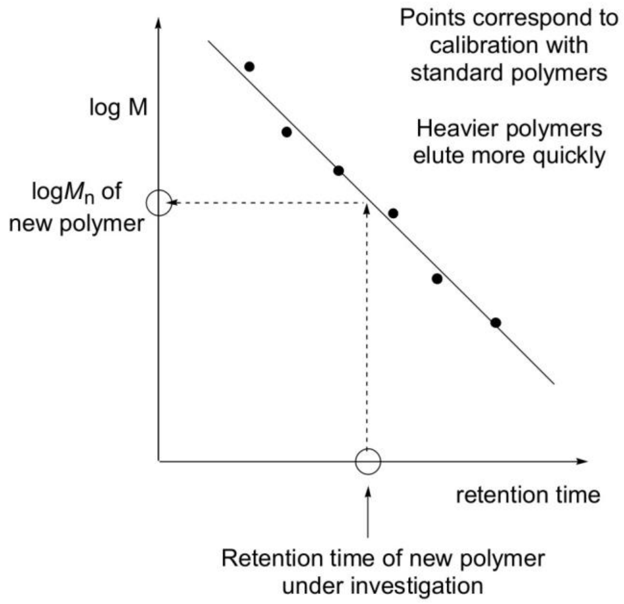
B) A bimodal distribution with a high polydispersity high mass polymer and a low polydispersity low mass polymer;

C) An asymmetric polymer distribution with high polydispersity and more high mass polymers than low mass polymers.

HINT remember that heavier polymers elute first.



If a polymer has a symmetric mass distribution, then M_n can be determined from the peak maximum. Importantly, however, we need to know how to convert the *time* of elution into the *mass* of the polymer.



GPC is not an absolute method and the column/equipment has to be calibrated. This is done by injecting well-defined polymer standards of known M_n values. The **retention times** of these polymers are plotted against **log M** to give a straight line (see graph). The calibration line can then be used to calculate the mass of an unknown polymer with a known retention time (or predict retention time of a polymer with known mass).

YOU do the work. Polystyrene standards were used to calibrate a GPC machine and had retention times as shown in the Table below. By drawing an appropriate graph, estimate the M_n value of an unknown sample of polystyrene which has a retention time of 18 min, 45 sec.

Polystyrene Standard M_n	**Retention Time**
5000	21 min 30 sec
10000	20 min 0 sec
25000	18 min 0 sec
50000	16 min 30 sec
100000	15 min 0 sec

HINT Your graph should be a straight line plot. Be careful with your units for time.

Paste your graph in below:

Do not just sketch it – draw it accurately using graph paper or a computer).

Check Your Answer (M_n = ca. 17800)

Strictly speaking, however, polymers with different shapes and structures will have slightly different calibration curves (because of their slightly different molar volumes), and so care must be taken to ensure that the standard polymer chosen for the calibration is reasonably similar to the unknown polymer you are wishing to analyse.

GPC is also able to give information about M_w and polydispersity. The M_w value can be calculated by computer programs which fit the line shape of the time/mass distribution. This approach also has to be used to calculate M_n if the mass distribution is asymmetric, because the peak maximum will not necessarily correspond to the number average molecular mass. The polydispersity is also calculated via computer fitting.

3 SYNTHESISING POLYMERS

A CHAIN POLYMERISATION

Chain polymers account for a large proportion of the synthetic polymer industry. They are prepared from alkenes, and this can be done in one of three ways: **free radical** polymerisation, **cationic** polymerisatio**n**, **anionic** polymerisation In the first case, the **reactive chain end** is a free radical, in the second, the reactive chain end is cationic and in the third the reactive chain end is anionic.

In general, all of these chain polymerisations have the following common mechanistic features:

- **Initiation**. A reactive species is formed and attacks the first monomer molecule, generating a *reactive end group*.

- **Propagation**. The reactive end group reacts with further monomers sequentially to give a long polymer chain – which retains its reactive end group at each step along the way.

- **Termination**. The reactive end group is deactivated and polymerisation ends. If this does not happen, the polymer would grow infinitely.

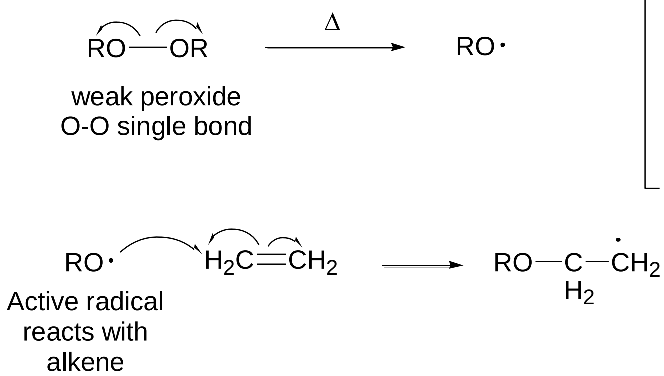
This process is somewhat like the dating game – with initiation being the first date (usually some sort of special event), propagation being the sequence of following dates (many of which can seem quite repetitive) and ultimately leading to termination, where the reactive end group of the polymer goes and does something else instead, and the relationship ends. (I am a romantic really – and not quite as cynical as that!).

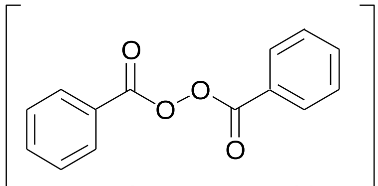
i. FREE RADICAL POLYMERISATION

In free radical polymerisation, the alkene double bond opens homolytically (one electron in each direction). To do this an **initiator with an unpaired electron** is required. Free radicals are very reactive species – therefore free radical polymerisation is generally useful for polymerising a wide range of different alkenes.

Initiation

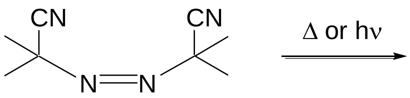
An ideal initiator is stable at room temperature but breaks down rapidly at the reaction temperature. Peroxides, in particular benzoyl peroxide, are popular. The weak O-O bond breaks generating reactive radicals that react with the electron rich double bond. The reactivity of benzoyl peroxide and its ability to break down into reactive radicals means it is sold over the chemists' counter as a treatment for acne (however, when used in this way, it does not initiate polymerisation, but rather uses the destructive power of radicals to react with anything).





benzoyl peroxide

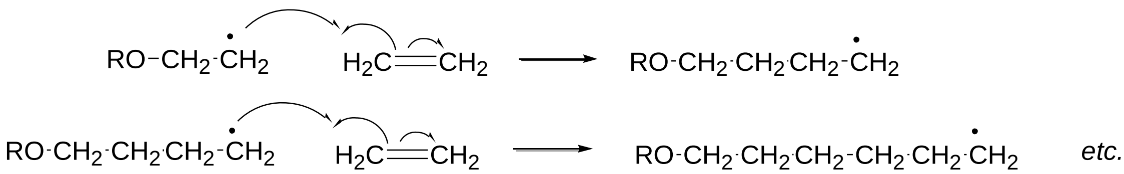
YOU do the work. Find/draw the curly arrows and reaction products for the breakdown of azobisisobutyronitrile (AIBN). This decomposes relatively easily, giving a free radical product, either by heating or by irradiation with UV light and is a very effective initiator. This initiator is very effective but hard to get hold of, as a few years ago, a container full exploded on a ship. Using your reaction scheme,



suggest why AIBN is both effective and potentially explosive!

Propagation

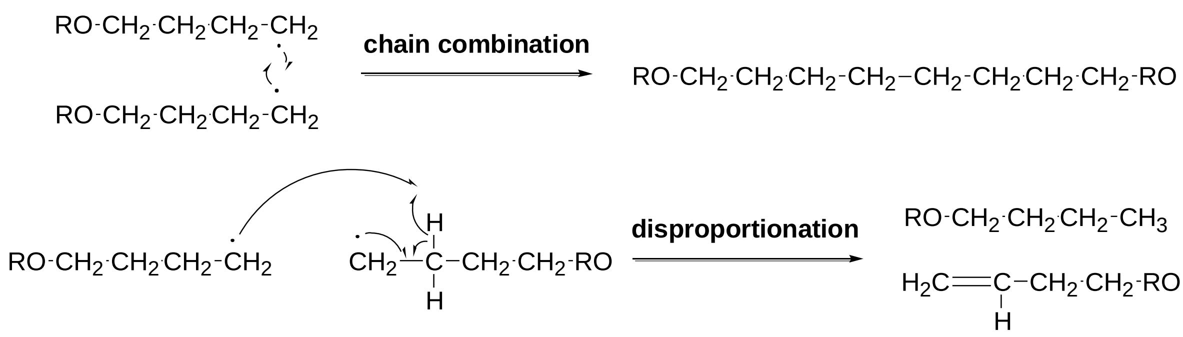
In each propagation step, the initiated radical adds to another molecule of the monomer, generating another **terminal radical** which can propagate further.



These radical based reactions are very fast. For example, it has been estimated that when styrene is polymerised at 373 K, one monomer adds every 0.75 ms, giving chains of over 1000 repeat units length in just one second. This also makes these reactions quite difficult to control.

Termination

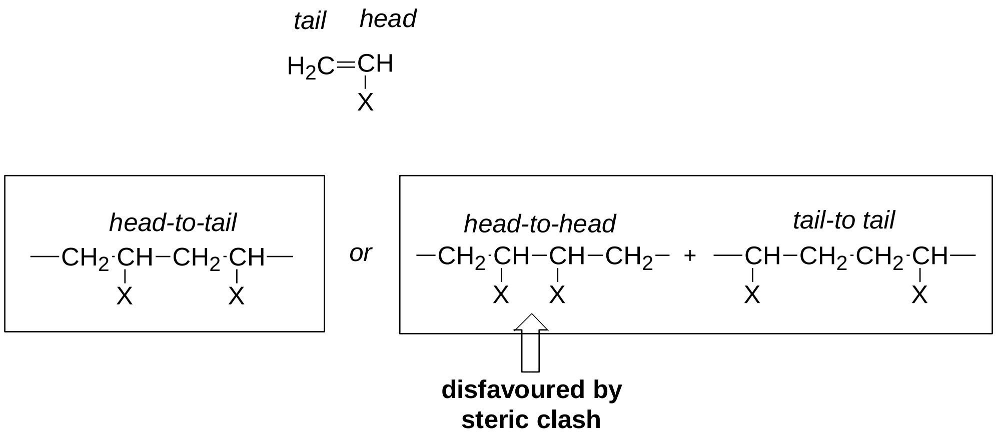
Termination of polymer growth occurs through two main mechanisms. The simplest method is chain combination, where two reactive radicals on different polymer chains react with one another to form a bond. Alternatively, and less commonly the reactive radical can abstract a hydrogen atom from a polymer chain – in this case, one chain is reduced to an alkane, while the other is oxidised to an alkene (a process referred to as disproportionation).



Growing polymer chains can terminate at any point in the propagation process and this is one of the reasons that polymers synthesised by free radical chain polymerisation are quite polydisperse.

Polymerisation of Substituted Alkenes

For substituted alkenes, they could either polymerise in a *head-to-tail* mode, or as a mixture of *head-to-head* and *tail-to-tail.* There is a marked preference for head-to-tail polymerisation. This is primarily for **steric reasons**.

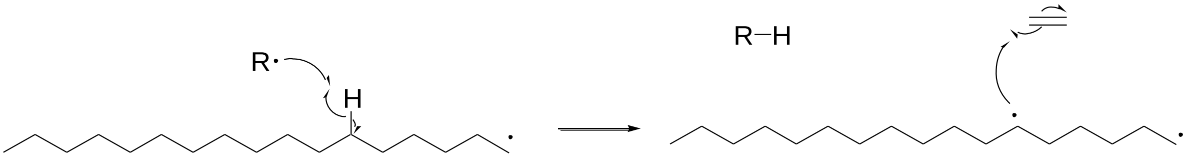


When the X-group is capable of stabilising a radical (*e.g.* Ph, which has resonance stabilisation, or Me which donates electron density into the half-filled orbital), then head-to tail coupling is reinforced. This is because the reactive radical on the growing chain terminus is stabilised, and therefore more energetically accessible – lowering the activation energy barrier for the reaction.

YOU do the work. Draw the reaction mechanism for the polymerisation of propene initiated by a generic initiator, I•.

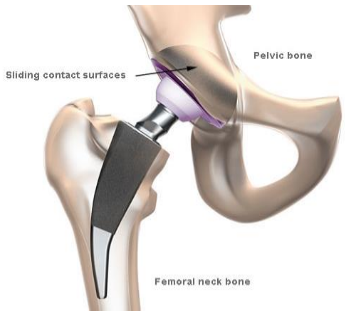
Branching of the Polymer Chain

One side reaction which free radicals can undergo, is to abstract a hydrogen atom from the **middle of a chain** (either its own chain or another chain). If this happens, then a free radical is generated in the middle of a polymer chain. This can act as a reactive site and initiate the growth of another polymer chain from that point. This leads to branching.



This branching can completely alter the properties of the polymer. For example:

High density polyethylene (polythene): no branching, the long, straight chain polymers can align and therefore they pack close together and make a dense strong material. Can be used to make the 'cup' in *artificial hips*.



Low density polyethylene (polythene): lots of short branches, therefore the polymer chains cannot get close together and the material is low density – very flexible. Used in *rubbish bags*.

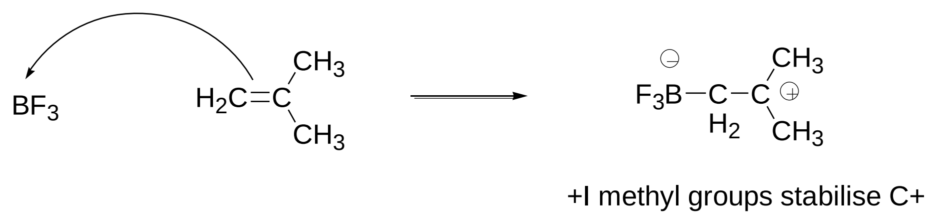
YOU do the work. In sketch form, show the polymer chains and their packing as found in high density and low density polythene.

ii. CATIONIC POLYMERISATION

In cationic polymerisation, an electrophile removes both electrons from the double bond producing a positively charged carbon atom on the propagating polymer chain. Cationic polymerisation is particularly successful with alkenes in which electron donating groups are attached to the double bond. These electron donating groups stabilise the carbocationic intermediate and lower the activation energy required for the reaction pathway, making it energetically accessible.

<u>Initiation</u>

The initiator is an electrophile which reacts with the electron rich double bond. In

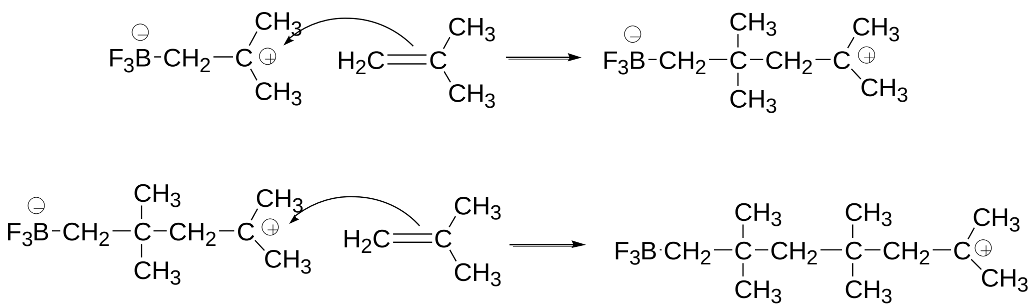


most cases Lewis acids (*e.g.* BF_3) are used as electrophiles.

A Bronsted acid such as HCl, would also initiate the reaction using H^+, *but* Cl^- would then act as a nucleophile and terminate chain growth immediately to give the normal Markownikov electrophilic addition product (see alkenes and alkynes course).

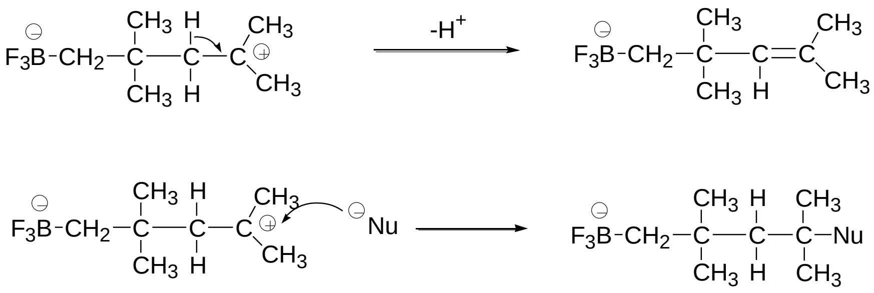
Propagation

Alkenes can keep adding to the cation on the terminus of the growing polymer chain. As with radical polymerisation, as the chain grows, the reactive site always ends up on the terminus of the chain. Note that the cationic centre at the reactive terminus of the chain will always be the most stable (i.e., energetically accessible) carbocation.



Termination

Termination is different in this case, and can occur by loss of a proton, or by addition of a nucleophile that caps the terminus of the polymer chain.



Cationic polymerisation therefore offers a way of controlling the termination process (and therefore the polymerisation reaction) more precisely. By adding a nucleophile to the reaction at a controlled time, it is possible to cap the growth of the polymer in a fairly controlled way. The longer the time left before adding the nucleophile, the longer the polymer chains will grow.

YOU do the work. 1,1,2,2-tetrafluoroethene is a very poor substrate for cationic polymerisation – giving your reasons, explain why.

YOU do the work. Cationic polymerisation of styrene can be achieved using $HClO_4$ as a catalyst and occurs as outlined in the table below.

Solvent	**Dielectric Constant**	**Catalyst**	**Propagation Rate (arbitrary units)**
CH_2Cl_2	9.7	$HClO_4$	17.0
80/20 CH_2Cl_2/CCl_4	7.0	$HClO_4$	3.2
60/40 CH_2Cl_2/CCl_4	5.2	$HClO_4$	0.4
CCl_4	2.3	$HClO_4$	0.0012

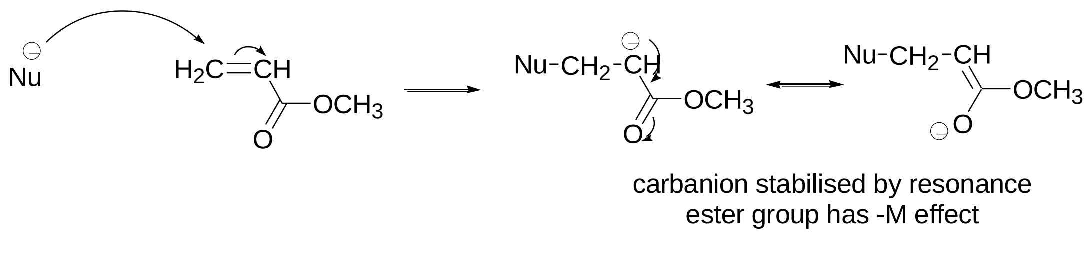
1. Explain why $HClO_4$ is a more suitable catalyst for cationic polymerisation than HCl.
2. Explain why the reaction gets slower as the polarity (dielectric constant) of the solvent decreases.

If you have problems with this, why not go on the forum and chat about it with other students on the course. If you cannot sort things out, the course leader may get involved and help out.

iii. ANIONIC POLYMERISATION

In anionic polymerisation, a **nucleophile** adds to the double bond increasing its electron density and giving a negatively charged carbon on the propagating polymer chain. **Nucleophiles do not normally add to double bonds** (see alkenes and alkynes course) – therefore the double bond **must** have a strongly electron withdrawing group attached to it for this mechanism to occur. Furthermore, the initiator must be a **very reactive nucleophile**.

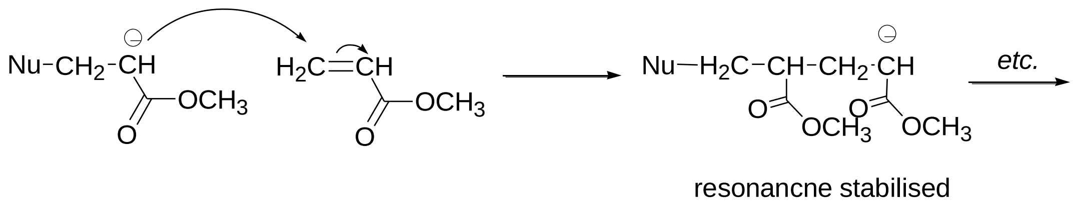
<u>Initiation</u>



In this example, anionic polymerisation occurs because of the –M stabilising effect of the carbonyl group. This stabilises the anionic chain terminus by resonance, and makes it energetically accessible. Other good substrates for anionic polymerisation are halogen substituted alkenes: the halogen groups offer –I stabilisation of the carbanionic intermediate.

Propagation

Propagation occurs in the predictable way with the reactive chain terminus adding to another equivalent of alkene:



Termination

Perhaps the most remarkable and useful feature about anionic polymerisation is that the chain **does not terminate**. It can only be terminated by reaction with the solvent, or with an impurity in the reaction mixture, or if an electrophile is added. If the solvent cannot donate a proton to the chain and all impurities are rigorously excluded then chain polymerisation will continue until all the monomer has been consumed.

The reactive site will then **still be active** so if more monomer is added the reaction will continue. The polymerisation is said to be **living**.

Living Polymerisation

In living polymerisation, the initiation step is faster than propagation and therefore all initiators start a polymer chain growing, and all polymer chains then grow (propagate) smoothly at the same average rate. This allows us to **predict and control the way in which polymer chains will grow**, and to synthesise well defined (nearly perfect) polymers. Generally, the products from **living polymerisation** are very **well defined** and have low **polydispersity values (<1.1)**.

WORKED EXAMPLE. Imagine a model living polymerisation, with 1 mole of monomer molecules (A) and 0.1 moles of initiator.

Therefore 0.1 moles of monomer will be initiated (by the 0.1 moles of initiator) and will start to grow 0.1 moles of polymer chains.

The chains will grow smoothly with the remaining monomer. Statistically, on average, each chain will grow to a predictable chain length with the monomer being shared out equally between all of the initiated polymer chains.

Chain length = [monomer]/[polymer chains]

= [monomer]/[initiator]

In this case chain length = 1/0.1 = 10

Product = $A\text{-}A\text{-}A\text{-}A\text{-}A\text{-}A\text{-}A\text{-}A\text{-}A\text{-}A^{-}$

Notice that the terminus of the chain is still anionic (i.e., still living).

If a second monomer (B) is then added (2 moles), then each chain will grow further:

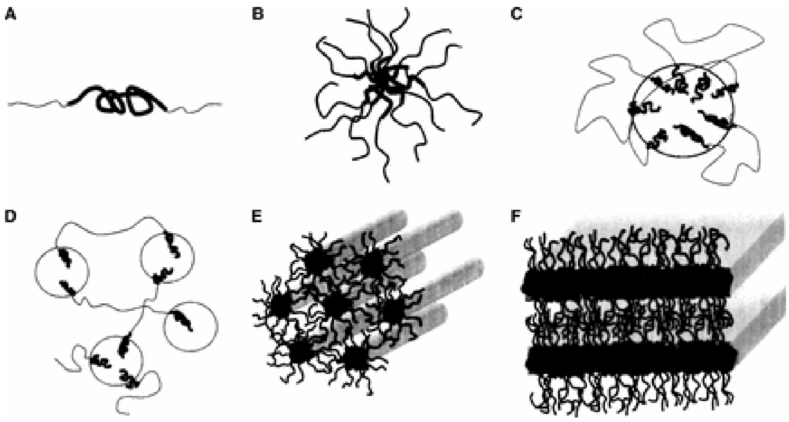
Chain growth = [monomer]/[polymer chains] = 2/0.1 = 20

Product = A-A-A-A-A-A-A-A-A-A-B-B-B-B-B-B-B-B-B-B-B-B-B-B-B-B-B-B-B-B$^-$

(A_{10}-B_{20})

YOU do the work. Monomer A (20 mmoles) is treated with initiator (0.05 mmoles) and allowed to react in a living polymerisation for 1 hour, until reaction is complete. Monomer B (5 mmoles) is then added to the solution and stirred for 1 hour. Monomer C (20 mmoles) is then added, the reaction proceeds for 1 hour until complete, and the product is then isolated by gel permeation chromatography. What is the structure of the product?

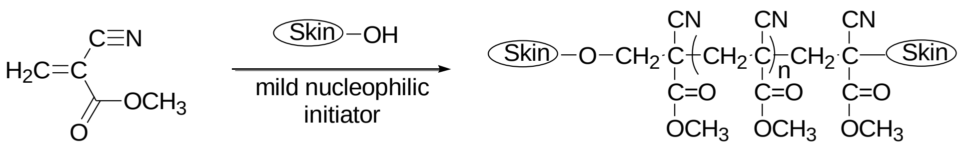
The products of these reactions are called **block copolymers**. Co-polymers contain two different monomers, block co-polymers have them organised into two separate segments. Block co-polymers are useful because each block can have quite different properties, providing the polymer with a unique blend of characteristics. For example, block co-polymers with hydrophilic and hydrophobic parts can organise themselves into all kinds of interesting nanostructures when placed in a hydrophilic environment such as water. These structures have potential applications in nanomedicine.



Super Glue

Superglue is a made by anionic polymerisation from the monomer shown below. This monomer does not need to be initiated by such a strong nucleophile – in fact, an OH group of a sugar or a protein is nucleophilic enough to act as an initiator. This is why superglue sticks skin together so well – protein on the surface of your fingers initiates the polymerisation, the covalent polymer chain then grows between the two skin surfaces and holds them together.

Superglue is actually used in battlefield surgery (and even in a hospital setting) as it provides an effective way of quickly sealing a wound.



YOU do the work. Can you explain why the superglue monomer is so reactive that it can react with mild nucleophilic initators such as skin?

HINT: Think about electronic effects.

Polymer Stereochemistry

As well as having different lengths, polymer chains can also have different stereochemistries. Consider the poly(propene) (shown below).

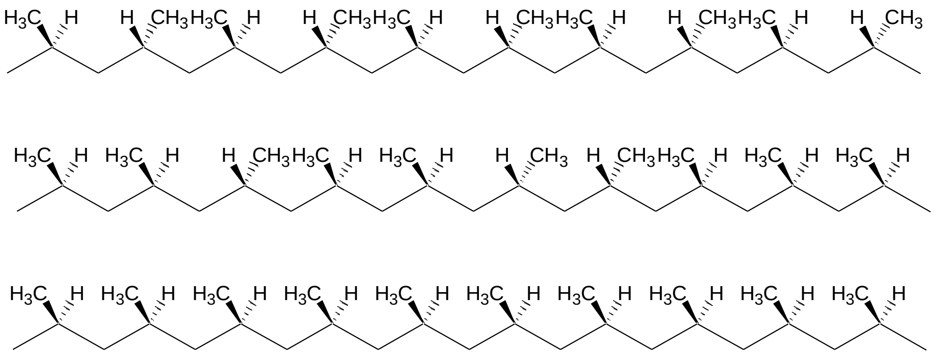
Atactic polymer - methyl groups are randomly oriented on both sides of the polymer chain.

Isotactic polymer – all methyl groups are on the same side of the fully extended carbon chain.

Syndiotactic polymer – the methyl groups regularly alternate on both sides of the carbon chain.

The same principles apply to any polymer with an X group (instead of Me) substituent.

YOU do the work. Label the three polymers below as atactic, isotactic and syndiotactic.



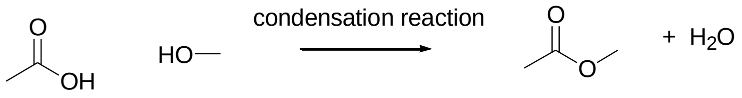
The structure of the polymer depends on the mechanism by which polymerisation occurs. In general, radical polymerisation gives rise to atactic polymers, cationic polymerisation gives a considerable amount of isotactic or syndiotactic polymer. Anionic polymerisation gives the greatest stereoregularity – especially at **low temperatures**.

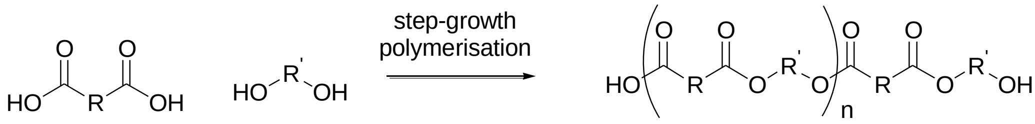
Ziegler-Natta catalysts (aluminium-titanium based) can be used to obtain long chains of either isotactic or syndiotactic polymer. Well-defined stereoisomers have different physical properties because the chains can pack more efficiently in the solid state. Such polymers therefore have a greater degree **of crystallinity**.

B STEP GROWTH POLYMERISATION

The formation of step growth polymers is dependent on multiple condensation reactions.

Let us consider a typical step growth polymerisation based on the reaction between carboxylic acid and alcohol, to give an ester.

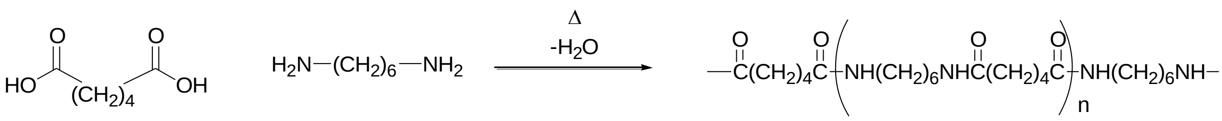




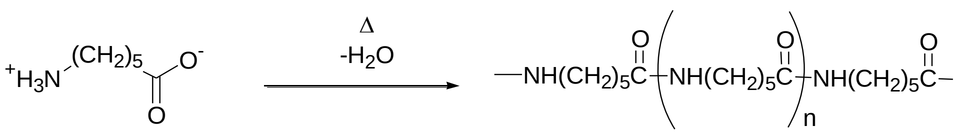
Polyesters have found widespread use as fibers, plastics and coatings.

The formation of step growth polymers does not involve chain reactions. Any two monomers can react and as a consequence, in step growth polymerisation, very many short chain polymers will form. The relative molecular mass of such a polymer will only exceed 10000 if the monomers are pure **and** in precisely equivalent proportions, and the polymerisation is a **high yielding reaction**.

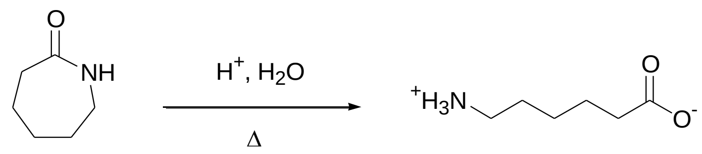
One of the most important types of step-growth polymer are polyamides. One of the simplest types of nylon to make is called **Nylon 66**. The polymer is so-named because a six-carbon diamine reacts with a 6 carbon diacid (the first number always refers to the amine and the second to the acid):



There are also other ways of synthesising nylons, other than reacting a diamine and a diacid. The other methods involve the condensation of a single difunctional monomer containing both acid and amine groups:



This polymer is called **Nylon 6** because it is formed from the polymerisation of a single compound containing 6 carbon atoms. It should be noted that this reaction is structurally similar to the polymerisation of α-amino acids to form proteins. The starting material for nylon 6 is the ring compound ε-caprolactam. The ring is opened by hydrolysis and then polymerisation of the open chain compound occurs.



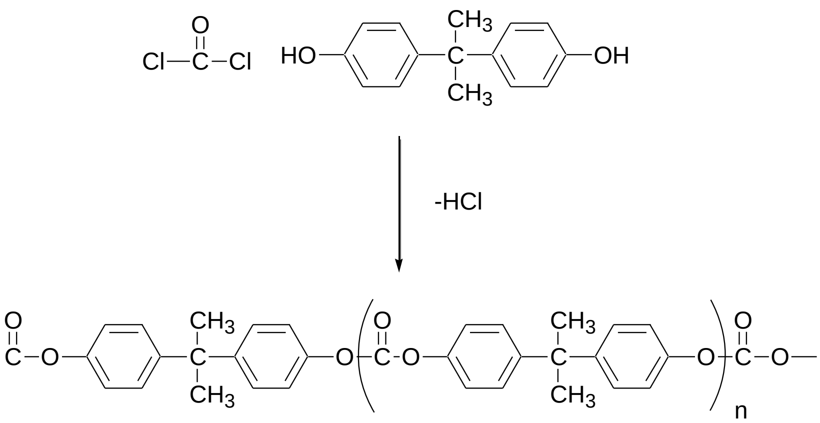
YOU do the work. Perhaps the most famous synthesis of nylon, which many of you will have done at school, is the 'Nylon Rope Trick'. Take a look at it, you can find videos of this online – search on YouTube. Write a reaction scheme and explain carefully what reagents/solvents are used and how this reaction (trick) is performed.

Other Step-Growth Polymers

Other important classes of step-growth polymers are **polycarbonates** and **polyurethanes**.

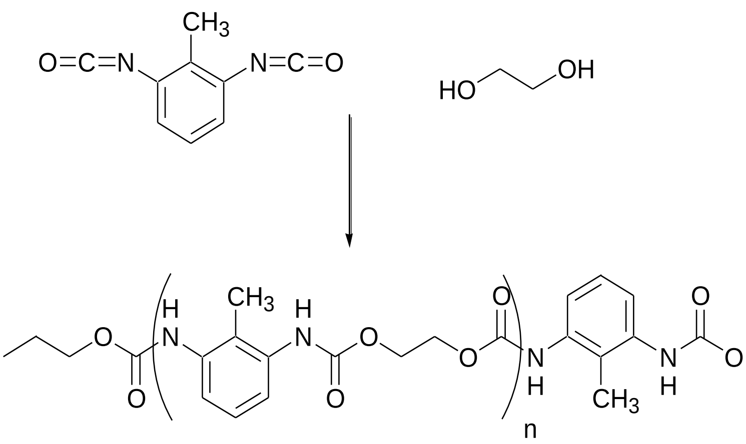
YOU do the work. On the structures, sketch the *reaction mechanisms* for polymerisation:

HINT: You need to find nucleophiles and electrophiles in the reagents and draw curly arrows. Remember the Organic Reactions and Mechanisms Course.



polycarbonate

Applications:



polyurethane

What is an alternative name for the 'urethane' functional group?

Comparing Chain Polymerisation and Step Growth Polymerisation

A Chain Polymerisation	**B Step-Growth Polymerisation**
Growth by addition of monomer only at one end of chain	Growth from both ends of chain
Different mechanisms operate at different stages of reaction (initiation, propagation, termination)	Same mechanism throughout
Molar mass of chain increases rapidly	Molar mass increases slowly throughout
If termination takes place the chains cannot grow further	Ends remain active (no termination step)
Initiator required	No initiation necessary

C OTHER POLYMERS

It is not only organic compounds which can be polymerised. It is possible to form polymers from a wide range of elements. Some examples are included below.

Sulfur

Liquid sulfur above its melting point of 392 K and below 432 K contains oligomeric ring molecules (S_6 - S_{26}), many of which have been prepared and characterised independently.

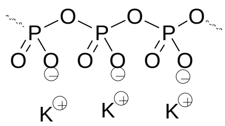
An **oligomer** is a polymer-like molecule, but of shorter (and usually defined) length.

Above 432 K, liquid sulfur also contains polymer chains (plastic sulfur). This is the form of sulfur usually found in volcanoes, and volcanic vents under the ocean.

Polyphosphates

Synthetic polyphosphates can be synthesised according to the equation below.

$$KH_2PO_4 \xrightarrow{\text{heat}} 1/x\ (KPO_3)_x + H_2O$$



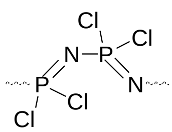
YOU do the work. What are polyphosphates used for?

Perhaps the most famous polymer that includes a phosphate link, however, is DNA. Although DNA is a polymer in which the backbone consists of sugar-phosphate-sugar-phosphate etc. You will learn more about DNA in the courses on biological chemistry.

Polyphosphazenes

Combining nitrogen and phosphorus it is possible to make polyphosphazene – which was demonstrated to have the same properties as rubber.

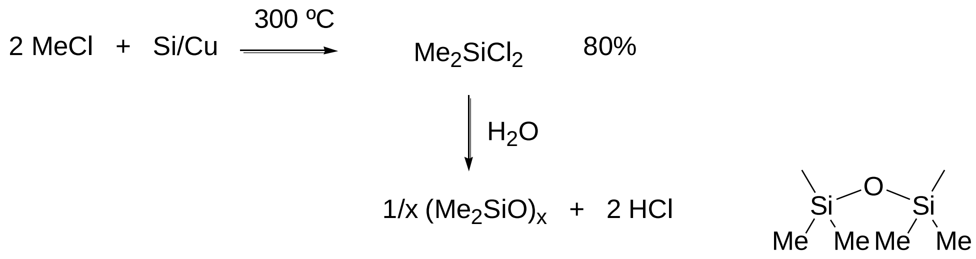
$$PCl_5 + NH_4Cl \xrightarrow{\text{heat}} 1/x\ (NPCl_2)_x + 4HCl$$



Inorganic Rubber

Polysiloxanes (Silicones)

Perhaps the most widely applied polymers without carbon atoms in their backbones are polysiloxanes. The Si-O-Si linkage has long bonds and is very flexible (bonds are easily able to rotate) meaning the polymer chains are readily mobile. This controls the physical properties of the polymer



YOU do the work. Give *three* applications of polysiloxanes (silicones).

4 POLYMER PHYSICAL PROPERTIES AND APPLICATIONS

The most interesting aspect of polymers is that they have highly tunable and useful material properties. They also have some unique forms of physical behaviour, which we need to consider in more detail.

The Glass Transition Temperature

For non-polymeric compounds, there are three standard states of matter – solid, liquid and gas. In a solid, the atoms/molecules are fixed in space and able only to vibrate, in a liquid, they are free to move, but still interacting with on another, and are therefore bounded by a meniscus, whereas in a gas, they have full freedom of translation, vibrational and rotational motion.

In polymers, however, the presence of long chain-like molecules leads to **two different kinds of solid**.

At sufficiently low temperatures, all polymers are **hard rigid solids** – referred to as **glassy**. These are equivalent to molecular solids. The polymer chains are essential fixed, and the only motion corresponds to the vibration of individual bonds/atoms within the polymer chain.

As the temperature increases, increasing amounts of energy are given to the polymer. This allows segments of the polymer chain to being to move cooperatively. This is a kind of partial translational motion – or can be considered as an extended chain-based vibration. At this point, the increased mobility of the material allows it to be compressed/expanded, and as such it behaves like a **rubber**. The point at which a polymer converts from a **glass** to a **rubber** is called the **glass transition temperature**, T_g.

If we continue to heat the polymer, eventually the polymer chains will achieve free translational motion – and at this point, the polymer will begin to behave as a **liquid**. The temperature at which this occurs is, like in any solid-liquid transition, referred to as the **melting temperature,** T_m.

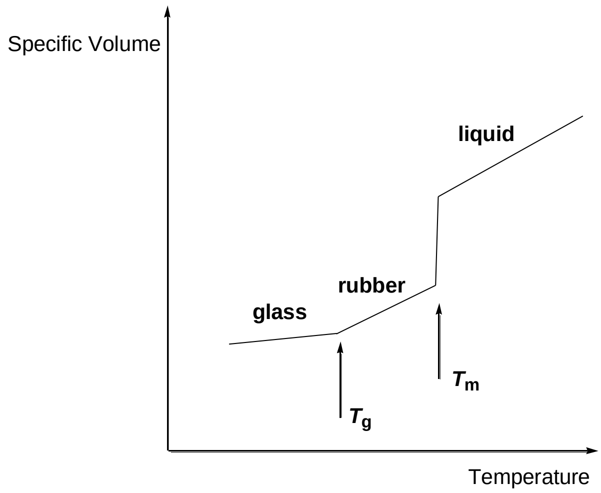
Most polymers cannot be converted into gases as they are heated further. They are such large molecules it would take too much energy to make the polymer chains move completely independently of one another. If this much energy is put in, then covalent bonds typically begin to break and the polymer will decompose instead.

The scheme below outlines the effect of heating a polymer.

Molecular motion	Behaviour
Vibrations of atoms about equilibrium positions	Behaves like a hard glassy solid
⇩ ***ENERGY***	
Motions of a few atoms (5 or 6) along the main chain	
⇩ ***ENERGY***	
Cooperative wriggling and jumping of segments (40 to 50 atoms)	**Behaves like a rubbery flexible solid**
⇩ ***ENERGY***	
Translational motion of entire molecules allowing flow	**Behaves like a liquid**

YOU do the work. Find two polymers which are in the rubber state at room temperature (T_g<25°C), and two polymers which are in the glassy state (T_g>25°C). State what they are applied for.

Glass transition temperatures can be measured analytically by determining the change in a polymer property with temperature. Typically **polymer volume**, **refractive index**, or **heat capacity** are used. Each of these polymer properties undergoes a change in gradient at T_g. It is easiest to understand this effect by considering polymer volume.



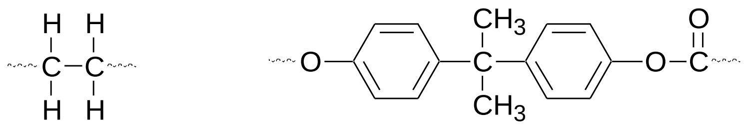
The glass is hard and not easily compressible. Therefore even when the temperature is changed quite a lot, the volume does not change very much (low gradient). However, on changing from a glass to a rubber (T_g), the material becomes much more compressible (springy). Therefore, applying thermal energy can lead to quite a large change in volume (hence the gradient for the rubber is steeper). On melting (T_m), the crystalline packed polymer chains separate from one another as they gain translational mobility, and there is therefore a step change in the specific volume.

Controlling the Glass Transition Temperature

Perhaps the most exciting feature of polymers is their widespread use in modern society. Bulk polymers are used in many different ways, and traditionally, applications have depended on the physical properties of the polymer. Can we understand the way in which the structure of a polymer controls the physical properties and potential applications?

The glass transition temperature depends on a number of properties, and this allows us to **control the behaviour** of our polymers by tuning their molecular structures. (N.B. These factors also have similar effects on the melting points of polymers)

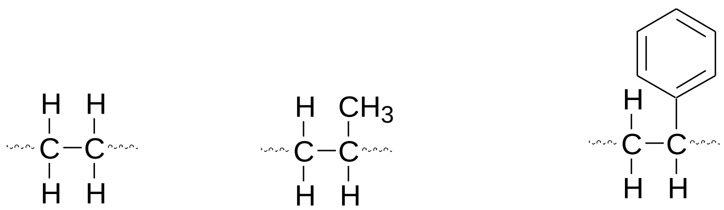
- **Polymer Backbone Flexibility**. Polymer main chains that cannot coil/move easily have higher T_g values. Single bonds are more conformationally mobile than multiple bonds/aromatic rings.



T_g = -120 °C — Flexible single bonds

T_g = +150 °C — Aromatic rings prevent chain flexibility

- **Effect of Rigid Side Chains on Polymer Backbone Mobility**. The more easily the polymer chain can rotate, the less energy is required to produce motion. Steric hindrance caused by rigid side chains will reduce the mobility of the



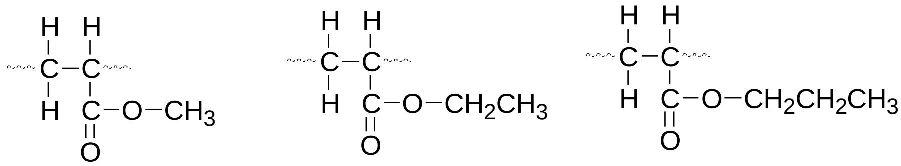
T_g = -120 °C — Flexible

T_g = -15 °C — Some steric hindrance

T_g = +100 °C — Lots of steric hindrance

whole polymer and hence increase T_g and T_m.

- **Effect of Large Flexible Side Chains on Polymer Packing**. Large, flexible side chains can prevent the effective packing together of polymer main chains in the bulk, and hence give increased overall mobility to the polymer (lower T_g).



T_g = +10 °C **T_g = -22 °C** **T_g = -44 °C**

Large flexible side chain hinders polymer packing

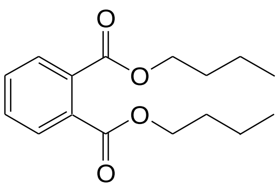
- **Attractive Forces Between Molecules**. The more strongly the polymer molecules interact with one another (*e.g.* polar polymers interact through dipole-dipole interaction, hydrogen bonding polymers through H-bond formation etc), the more energy is required to separate the polymer sand allow segments to move. Hence attractive forces between polymer chains raise T_g and T_m.

T_g = -15 °C **T_g = +87 °C**

-I effect of Cl atom leads to dipole-dipole attraction between polymer chains

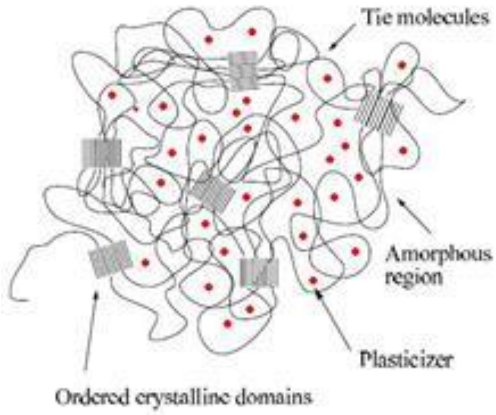
- **Chain length**. As the chains get longer, T_g increases because it takes more energy to get longer polymers moving.

- **Plasticisers.** By adding a plasticisers (small molecules), the polymer chains can be kept apart – increasing the free volume and decreasing interactions between the chains. This decreases the T_g and softens the polymer. Plasticisers are chosen because they interact well with the polymer chains and do not leach out of the polymer sample. But they are controversial – this is one of the potential topics for the independent presentation (see end of course).

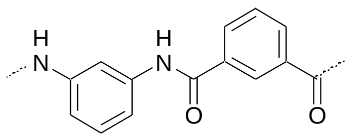


dibutylphthalate

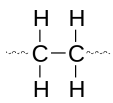
a (controversial) plasticiser



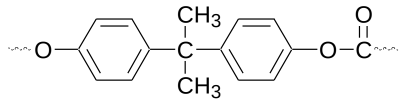
YOU do the work. Fully explain the glass transition temperatures of the following polymers:



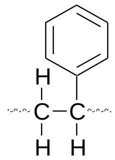
T_g = +546 °C



T_g = -120 °C



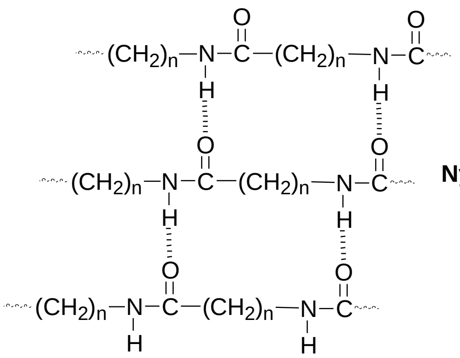
T_g = +150 °C



T_g = +100 °C

Hydrogen Bonding – Nylon and Kevlar

Nylons contain multiple amide groups. An amide is both a **hydrogen bond acceptor** and a **hydrogen bond donor**. They are tough materials (hence an 'improvement' on silk in stockings) primarily as a consequence of extensive hydrogen bond interactions between adjacent polymer chains.

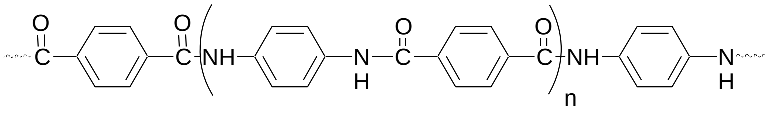


Nylon n

YOU do the work. Giving your reasons, suggest why polymer A has a T_g value which is 150°C higher than that of polymer B.

Polymer **A** Polymer **B**

Kevlar is also a polyamide, but in addition to the extensive inter-chain hydrogen bonding the main polymer chains themselves are made up of rigid aromatic rings. The result is a polymer so tough it is bulletproof – being used as the flak jackets typically worn by policeman and war correspondents. The tensile strength of this polymer is greater than steel, and because of its extreme temperature stability, it is used in protective clothing for firemen.

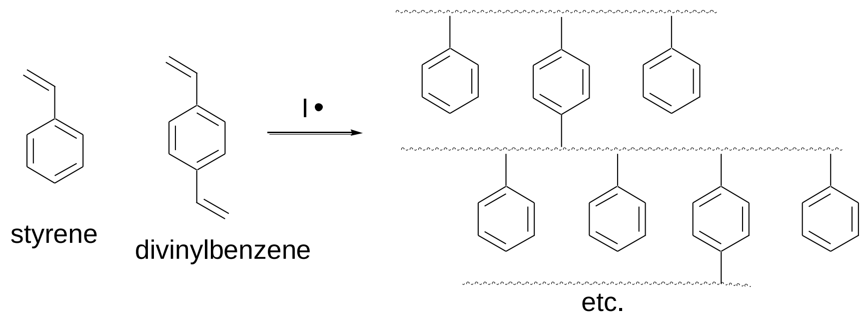


Kevlar

YOU do the work. Sketch the interchain hydrogen bonding which helps align Kevlar polymer strands and provide enhanced stability.

Cross-Linked Polymers

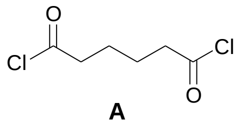
One way of enhancing the physical strength of polymers is to 'cross-link' them covalently. This can be achieved by using additives that have more polymerisable groups than they actually need. Such additives can get involved in more than one



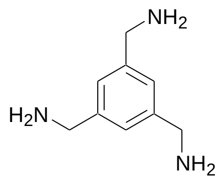
polymer chain, and therefore link them together covalently.

In the example above, styrene has one polymerisable alkene group, whereas divinyl benzene has two separate polymerisable group. This means that the two alkenes on divinylbenzene can become **independently involved in two different polymer chains**. In this way, divinylbenzene acts as a crosslinker, connecting the different polymer chains together. The more divinylbenzene is present in the reaction, the more crosslinking between polymer chains there will be.

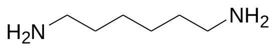
YOU do the work (i). Explain how compound **C** can act as a crosslinker in the step-growth (condensation) polymerisation of compounds **A** and **B**.



A



C

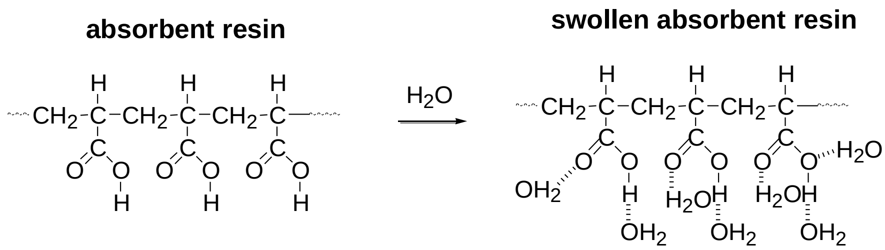


B

YOU do the work (ii). Suggest how the physical properties of crosslinked polymers, such as T_g and T_m, will change as the % of compound **C** used in the reaction is increased from 0% to 25%.

Superadsorbent Polymers

These are based on crosslinked polymers which contain very hydrophilic groups, such as *polyacrylic acid*. The presence of crosslinking prevents the polymer chains from simply dissolving in water. These polymers interact very well with water because they can form **multiple hydrogen bonds** and therefore on wetting, they



can adsorb large numbers of water molecules and swell dramatically.

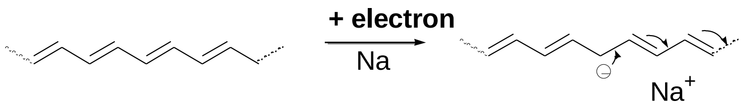
YOU do the work. Find two different applications of polyacrylic acid.

High Tech Applications of Polymer Technology

Increasingly, polymers are not only being investigated for their 'low-tech' applications as packaging and building materials, but are being exploited for their ability to generate very high tech multi-functional materials. There are many different examples of this, but a few are listed below with very brief details. Investigating one of these topics in more detail may be the focus of your independent presentation work.

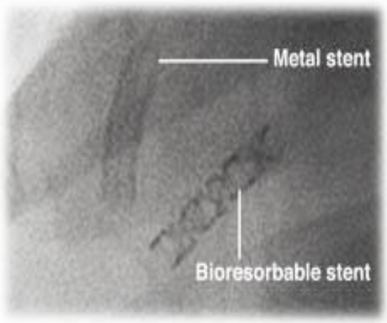
Liquid Crystalline Behaviour. Rigid rod-like polymers can exist in a phase which is intermediate between solid and liquid, and has characteristics of both. This is the so called liquid-crystal phase. Different to the rubber phase, the liquid crystal phase exists when polymers are aligned with one another to some extent (order), but still mobile (disorder). By switching this state on and off with an electric potential it is possible to generate display screen technology.

Conducting Polymers. The **Nobel Prize in the Year 2000** was awarded for the field of polymer electronics. Polymers are usually thought of as electrical insulators, and electrical wiring round the world is now sheathed in plastic. But conjugated polymers, can be thought of as being like molecular scale wires, and under the right conditions they can conduct electricity.



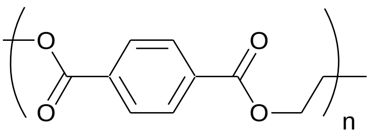
In addition, when excited electrically, these polymers can emit light – which has exciting possible applications in thin film display screens.

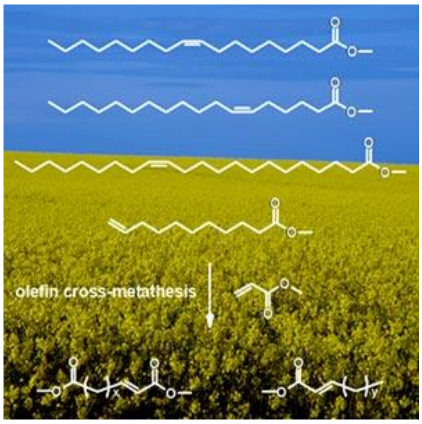
Polymers as Biomaterials. Careful molecular design allows the synthesis of next generation biomaterials. These can be implanted during surgery, and are sufficiently biocompatible that cells can grow over them and they can be fully accepted by the human body. Furthermore, they can be designed to degrade over time (like dissolvable stitches) so that once they have done their job in the body and allowed the body to regrow and regenerate its own tissue, they disappear and leave no trace. For example, this is one way proposed for the improved treatment of coronary artery disease.



Environmentally Degradable Polymers. There is significant concern about the role of polymers in the environment. In particular, waste packaging materials are a significant concern, with many of them going to landfill (or not) and causing long term environmental hazards. One approach is to design new polymers that will **biodegrade**. Such polymers can be broken down into small segments by enzyme catalysed reactions, or in the presence of oxygen. Cleavable bonds/functional groups have to be incorporated into the main polymer backbone. One good method involves placing ester bonds into the actual backbone of the polymer – the degradation of these weak links can be catalysed by enzymes.

Recyclable Polymers. Once again relying on the relative ease with which ester bonds can be broken, polymer recycling is becoming big business. The most important polymer for this is polyethylene terephthalate (PET) which is used in the drink and food containers. This polymer can be easily broken down and re-formed, with relatively low input of energy – therefore making it ideal for recycling.





Polymers from Green Feedstocks. The majority of feedstocks used to make plastics are derived from oil. This means that by definition, most plastics are not renewable, since oil is a finite resource which we cannot replace. In contrast, biomass is renewable: we can grow more plants to replace those that we use. We can derive chemicals, including monomers for polymer production, from biomass. Polymers made out of these monomers are therefore renewable polymers: they can be replaced by growing more biomass and repeating the manufacturing process. Although of course this has impacts on other uses of biomass, such as food. Interestingly, this trend brings us in some way back to the early 19th century, where the only polymers being regularly used were natural polymers such as cotton, wool etc.

<u>Appendix 2</u>

TOPICS FOR INDEPENDENT INVESTIGATION

TOPICS FOR INDEPENDENT INVESTIGATION

1 Phthalates have been the subject of considerable controversy because of their use as plasticisers in a variety of applications such as childrens' toys. Present the scientific background to this issue and the evidence on which governments and parents are coming to decisions. (Focus on: Structure-Property Relationships).

2 Plastic packaging causes a serious problem as waste in the environment. You should present the advantages and disadvantages of using plastic packaging compared to alternatives such as paper. You should discuss advances in environmentally degradable plastics, how they work, and their advantages/disadvantages. (Focus on: Recycling).

3 In 2000, the Nobel Prize for Polymers was awarded for work on conjugated polymers. Explain the significance of this work and outline some of its potential applications which might transform modern technology. (Focus on: Structure-Property Relationships).

4 Chelates are vital in many human reactions especially in their role of carrying oxygen to cells in the respiration process or carrying atoms during photosynthesis. Explain how chelates enable polymers to be used in body into a range of applications in medicine. (Focus on: Coordinate Bonding).

5 It is increasingly important that we minimise our reliance on oil. Explain how the natural world can be used a source of building blocks for different types of polymers, and the advantages, disadvantages and applications of this approach. (Focus on: Recycling).

6 Biocompatible polymers might be useful inside the human body – for example as stents in cardiac surgery, hard-wearing plastic hips etc. Discuss the polymers used for such applications, the kind of testing which is important, how they compare with other materials, and whether they are long term implants or biodegradable. How is biodegradation achieved? (Focus on: Biodegradability and Biocompatability)

7 Polymers have played a vital role in making the modern world of high technology work – from smart phones to electric cars. Focussing on this kind of application, explain the contribution of polymers to the modern world. (Focus on: Branching in Polymers)

8 We are all encouraged to recycle our plastics, but is it a worthwhile exercise? What are plastics, which plastics can be recycled, how and where is it done in practice, how much energy does the process use and what are the recycled plastics transformed into. (Focus on: Recycling)

9 The fashion industry has often made use of cutting edge polymeric materials such as Spandex, Kevlar, Goretex, and even the high-tech swimming suits controversially used in the Beijing Olympics. You should explain the impact of polymers, natural and/or synthetic on clothing and give some insight into what the future might hold for high-tech fashion. (Focus on: Branching in Polymers)

10 The aviation and space industries rely on polymers to play a wide range of roles – from adhesives which hold jumbo jets together, to the heat resistant tiles on the space shuttle. Explaining their fundamental chemistry and properties, discuss the use and future potential of polymers and nanocomposite materials in aeronautics and aerospace. (Focus on: Polarity of Polymers).

11 Polymers in sport. You may wish to consider the impact of polymers in sporting endeavour. This could focus on a range of topics such as the materials used in sports clothing, the high-tech materials used to make yachts, bicycles etc., or the polymers used for protective gear in sports such as cricket and American Football. (Focus on Structure-Property Relationships).

12 ***Please feel free to suggest any other topics which you believe would make interesting investigations. Wither use the message board or email me to check your choice of topic is a good one. This can sometimes lead to the most interesting presentations!***

Appendix 3

MARKSCHEME FOR INDEPENDENT INVESTIGATION

MARKSCHEME FOR INDEPENDENT INVESTIGATION – FOR GUIDANCE (50 Marks)

Scientific Content and Accuracy (10 Marks)

The scientific content and accuracy were perfect	10
The scientific content was of an excellent level and highly accurate	8
The scientific content was very good and accurate	7
The scientific content was very good and mostly accurate	6
The scientific content was good and mostly accurate	5
The scientific content was acceptable and partly accurate	4
The scientific content was unacceptable and/or largely inaccurate	<4

Clarity of Scientific Explanations (10 Marks)

Outstandingly clear, fully understandable to general public, professional	10
Very clear and fully understandable	8
Very clear and understandable	7
Clear and mostly understandable	6
Clear and partly understandable	5
Not very clear and only understandable in parts	4
Unclear and difficult to understand	<4

Quality of Presentation – Figures/Illustrations (10 marks)

Outstanding quality – ideal use of figures to support the arguments	10
Very good quality – well chosen, varied figures supporting presentation	8
Good quality – useful figures, more variety or greater quality would help	6
Acceptable quality – some clear figures, but not very varied or eyecatching	4
Poor quality – low quality figures, poorly chosen	2

Quality of Presentation – Text/Language (10 marks)

Outstanding quality – perfect text/spoken language , perfectly explained	10
Very good quality – very good use of language	8
Good quality – good use of language – a few errors or unclear parts	6
Acceptable quality – use of language is understandable, but with major errors	4
Poor quality – many errors, difficult to understand/follow	2

Evidence of Reading Beyond this Package of Material - Referencing (5 marks)

Based on extensive background work	5
Very good level of investigation	4
Reasonable amount of background reading	3
Some evidence of background reading	2
No evidence of background reading	1

'Interest' of the Article/Presentation (5 marks)

Very interesting indeed offering lots of insight – professional level	5
An interesting presentation with very good insight	4
Quite interesting with some insight	3
Predictable and did not offer much insight	2
Not interesting	1

Appendix 4

QUESTIONNAIRE USED IN THE MAIN STUDY

Name:

A. Please describe up to three features of chemistry modules that most help you develop your knowledge and understanding of chemistry.

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B. Please describe up to three features of chemistry modules that make them enjoyable to study.

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C. Please indicate up to three modules you have particularly enjoyed at the Department of Chemistry.

....

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D. Please indicate up to three modules that have particularly helped you to develop your knowledge and understanding of chemistry at the Department of Chemistry.

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- Name part is optional and it will only be used by the independent researcher.

Appendix 5

STUDENT INTERVIEW QUESTIONS

Research Question: What are the students' views and experiences of the independent learning?

Interview Questions

IQ1: In what ways has the teaching on the Macromolecules course differed from the teaching on other courses?

IQ2: What have you liked most and what have you liked least about the approach and why?

IQ3: What skills have you developed as a result of taking the course, or have you developed any?

IQ4: How do you think the course has affected your learning of chemical ideas, and why?

IQ5: How did you find experience of being a researcher and presenting your findings? How did this affect your interest in chemistry?

IQ6: How did you manage your time on the course? Would you say you have spent more or less time on the course comparing to other courses? Do you think you were good at managing your time?

IQ7: Has your view of what "teaching" means changed as a result of taking the course? If so how has it changed?

IQ8: What have been the biggest challenges for you on the course?

IQ9: What would be your advice to the next year's students about the course?

IQ10: How representative do you think your views are of the group as a whole?

Appendix 6

DIAGNOSTIC QUESTIONS FOR STUDENT TESTS

Dear Participant,

Thank you very much for agreeing to take part in this research study.

I am a PhD student at the University of York and I am interested in the teaching and learning of chemistry at university level. In particular, I wish to investigate the effects of novel teaching approaches on students' learning of chemical ideas, and students' attitudes to chemistry as a subject as a result of participating in these approaches. The course leader is very interested in gathering data on the effects of novel teaching and has agreed that I can focus on the development of understanding of polymer chemistry (Macromolecules) through his course, in which students are required to create a video or write an article about polymer chemistry as part of the course.

To investigate understanding of chemical ideas about polymers, I have developed four questions which look at aspects of polymer chemistry that relate to everyday life. You will be asked to complete the questions before and after you take the polymers course in order to track the development of your understanding. The questions have been prepared with reference to the learning objectives of the Macromolecules course. They will hopefully stimulate you to think about the knowledge that you already have about polymers and their importance in everyday life.

The questions are not a formal test. They are intended to provide a database of students' understanding before and after taking the polymers course. All you need to do is to answer the questions to the best of your ability. If you are unsure, or do not know the answer, please say so. It should take you around 20 minutes to complete all the questions.

All the information that you give will remain confidential and will not be used for any purpose other than as data for the research study. However, I will provide a general overview of responses and send this to you.

Thank you very much for your help.

Yours Sincerely,

Mutlu Cukurova, PhD Student, Science Education Group, Department of Education, The University of York, UK.

Recycling Process

a) Recycling of plastics is given high importance in every developed country. Statistics show that the amount of recycled plastic increases constantly all over Europe.

Please give three reasons why recycling plastics is important.

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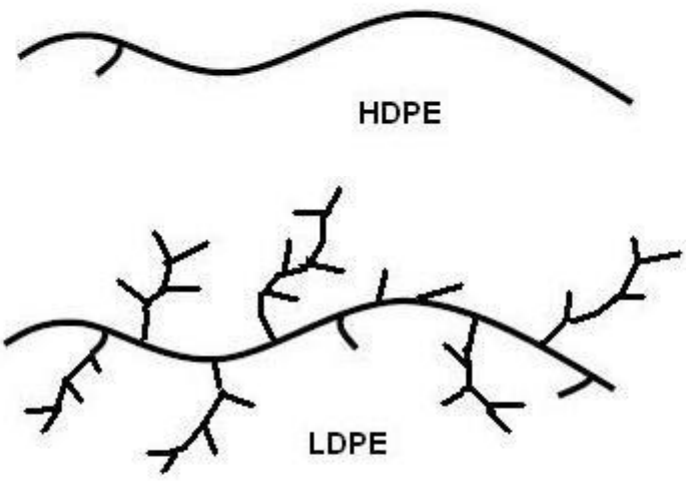
b) HDPE (High Density Poly Ethylene) and LDPE (Low Density Poly Ethylene) are two very common types of polymer used in industry to produce a variety of products. They are both recyclable and they both have good resistance to many chemical substances. LDPE is generally used for applications that need elasticity such as containers, dispensing bottles, wash bottles, tubing and plastic bags. HDPE is generally used for harder materials such as ballistic plates, chemical resistant piping systems, or home furniture.



Compare the two polymers in terms of tensile strength and resilience using the information and molecular structures given. Explain your reasoning.

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c) John's father works for a company which produces plastic bottles. John asks his father to bring him some pure HDPE and LDPE to experiment on them. He brings them to John who takes them to his school laboratory, puts them in porcelain crucibles and combusts them.

What do you expect him to observe at the end of the combustion as a final product of the complete combustion reaction? Explain your answers.

....

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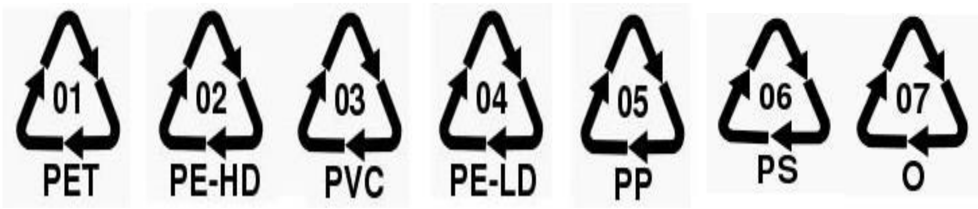
....

d) As can be seen below, plastics are identified with Plastic (Resin) Identification Codes (PIC) which should be written on the plastics.

Give three benefits of coding of plastics in this way.



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<u>Fashion and Fabrics</u>

a) Gore-Tex is the trade name of a polymer based material which is used in fashion, especially for winter clothing. The polymer is expanded poly (tetrafluoroethene) ePTFE, (Figure 1). The key feature of the material is that, although it is waterproof, it is also breathable which means the material does not let water get inside but it lets steam go out. Another commonly used polymer is Nylon (Figure 2) which has similar waterproof features but is not breathable. Different polymers have different uses depending on their characteristics. For instance, Gore-Tex material is ideal for making a jacket suitable for severe winter conditions; on the other hand Nylon would be preferred for parachute manufacture, since a breathable material would not decrease your velocity as effectively.

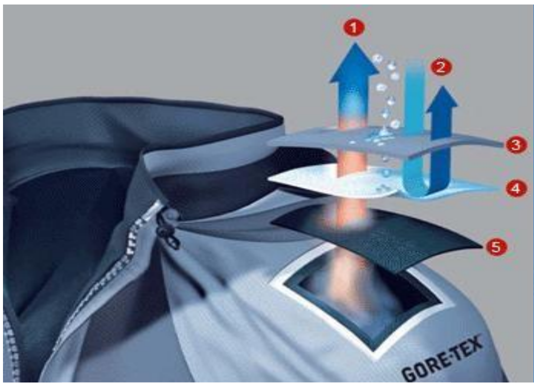

Image 1: Gore-Tex Jacket

Image 2: Parachute

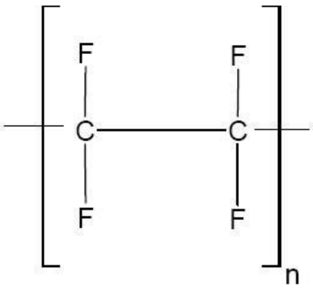

Figure 1: Poly Tetra Fluoro Ethylene

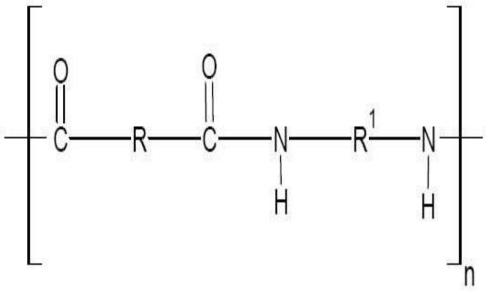

Figure 2: Nylon

Explain the waterproof and/or breathable characteristics of those fabrics using your chemistry knowledge.

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b) Gutta-Percha and Natural Rubber are cis- and trans- isomers of poly (isoprene) and are shown below. The structure of Gutta-Percha contains the trans-conformation (Figure 3) and the structure of natural rubber is the cis-conformation (Figure 4) of polyisoprene. The different conformations of isomers create different physical features of the materials. Because of the general tendency of materials towards minimum energy and maximum entropy, maximally dispersed configurations have more stable structures.

Using the information given deduce the two polymer's elasticity and brittleness at room temperature.

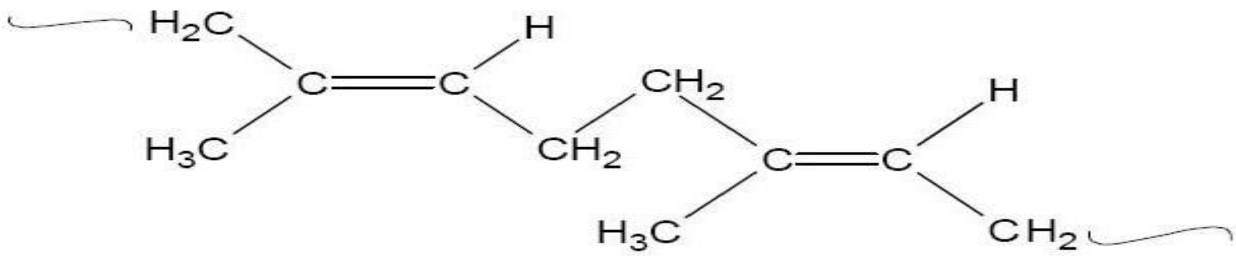

Figure 3: Trans-polyisoprene

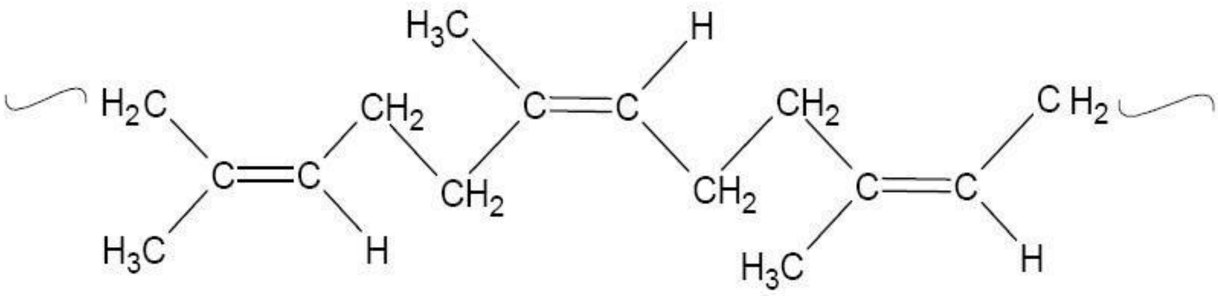

Figure 4: Cis-polyisoprene

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c) Kevlar is a synthetic polymer which can be synthesized through condensation polymerisation of para-phenylenediamine (1, 4-diaminobenzene) and teraphthaloyl chloride (1, 4 benzenedioyl dichloride). Kevlar (Figure 5) is used in various applications such as armour, sport equipments or audio equipment and on an equal weight basis Kevlar is approximately five times stronger than steel.

Explain where this strength comes from.

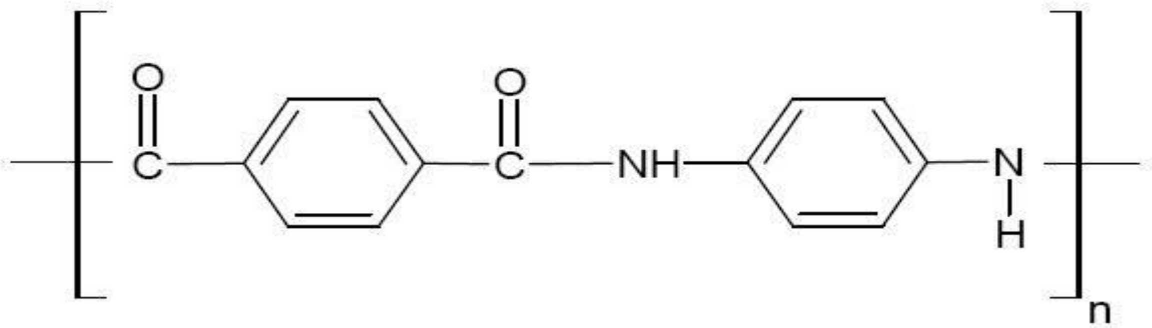

Figure 5: Kevlar

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d) Post-use processing is seen by scientists to be just as important as the production processes of polymers themselves since polymers' self-deterioration is normally quite slow. Although Kevlar is a very strong material and highly used in industry, one of the drawbacks of the material is its recycling. Because of its very high melting temperature (around 600 C^0) it decomposes before it melts.

Because of the fact that Kevlar's life is almost infinite when it disperses to landfill, and it is very hard to recycle, suggest another answer for the Kevlar that already has been produced in the past.

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This is the end of this test; please use this page to write your comments about the questions.

You may write any comment about the questions, also you may like to comment on:

The difficulty level of questions,

The clarity of the questions,

Thought-provoking features of the questions,

Similarities/differences of the questions compared with exam questions,

Practical features such as time management, paper, and print qualities, colours and the available space for answers.

Any information will be useful!

Thank you very much again for your time and help.

Dear Participant,

Thank you very much for agreeing to take part in this research study.

I am a PhD student at the University of York and I am interested in the teaching and learning of chemistry at university level. In particular, I wish to investigate the effects of novel teaching approaches on students' learning of chemical ideas, and students' attitudes to chemistry as a subject as a result of participating in these approaches. The course leader is very interested in gathering data on the effects of novel teaching and has agreed that I can focus on the development of understanding of polymer chemistry (Macromolecules) through his course, in which students are required to create a video or write an article about polymer chemistry as part of the course.

To investigate understanding of chemical ideas about polymers, I have developed four questions which look at aspects of polymer chemistry that relate to everyday life. You will be asked to complete the questions before and after you take the polymers course in order to track the development of your understanding. The questions have been prepared with reference to the learning objectives of the Macromolecules course.. They will hopefully stimulate you to think about the knowledge that you already have about polymers and their importance in everyday life.

The questions are not a formal test. They are intended to provide a database of students' understanding before and after taking the polymers course. All you need to do is to answer the questions to the best of your ability. If you are unsure, or do not know the answer, please say so. It should take around 20 minutes to complete all the questions.

All the information that you give will remain confidential and will not be used for any purpose other than as data for the research study. However, I will provide a general overview of responses and send this to you.

Thank you very much for your help.

Yours Sincerely,

Mutlu Cukurova, PhD Student, Science Education Group, Department of Education, The University of York, UK.

Bone Grafting Process

PCL (poly (caprolactone), Figure 1) is a synthetic material being used by scientists as a bone graft substitute *in vivo* (in the body of a living organism). The starting monomer, caprolactone, can be seen in figure 1.

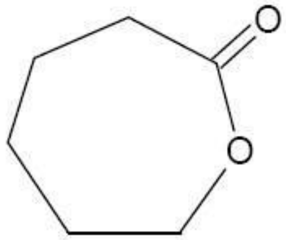

Figure 1: Caprolactone

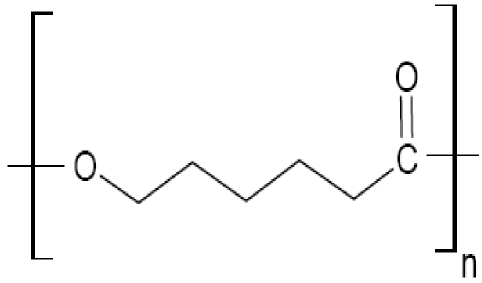

Figure 2: Repeating Unit of PCL

In a recent study, researchers have tried to use PVPA (poly (vinyl phosphonic acid-co-acrylic acid)) which is made from two different monomers vinyl phosphonic acid (Figure 3) and acrylic acid (Figure 4) with PCL as mixture of polymers to improve bone formation. The structure of the PVPA can be seen in figure 5.

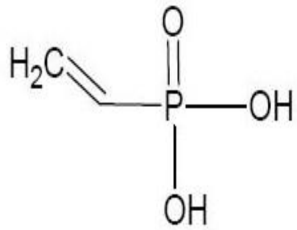

Figure 3: Vinyl Phosphonic Acid

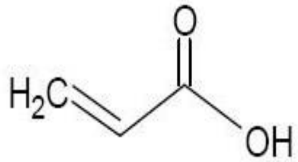

Figure 4: Acrylic Acid

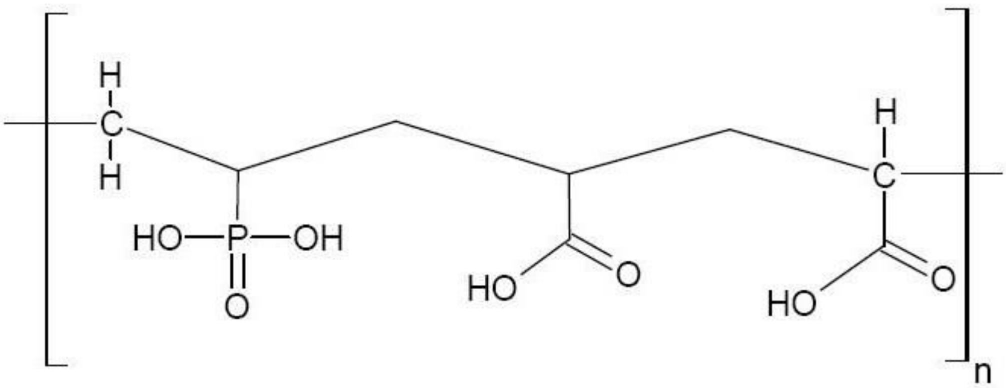

Figure 5: Repeating Unit of PVPA

a) Functional groups are atoms or small groups of atoms (usually two to four) that exhibit a characteristic reactivity when treated with certain reagents.

Name the functional groups in both polymers.

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b) Two important features of chemical materials used *in vivo* (in the body of a living organism) are biodegradability and biocompatibility.

Which features of the two polymers make them biocompatible and biodegradable in the body? Please explain your answer.

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c) A chelate is a chemical compound in the form of a heterocyclic ring, containing a metal ion attached by coordinate bonds to at least two non-metal ions. Chelates are vital in many human reactions especially in their role of carrying oxygen to cells in the respiration process or carrying atoms during photosynthesis. The possibility of forming chelates with the Ca^{+2} ions on the surface of bones made scientists hypothesize that adding PVPA can increase mineralisation, and therefore, promote osteoblast maturation. Osteoblasts are cells found in bone; their function is to form the tissue and minerals that give bone its strength.

Draw in the space provided below the possible chelate form of the PVPA polymer.

d) Another advantage of PVPA treatment (mixture) of PCL is that it increases the wettability of the PCL polymer. Because hydrophilic structure increases the likelihood of a polymer's reaction with water, wettability is a highly expected feature of all biodegradable chemicals. There is experimental evidence for the advantage of addition of PVPA over using PCL by itself, from the study of water contact angles of both polymers (see Table 2 below).

Explain the change of wettability of PCL when it is treated with PVPA.

Table 2: Water contact angle of PCL and PCL/PVPA scaffolds

	Material	Contact angle
A)	PCL	123.3 ± 10.8°
B)	PCL/PVPA	43.3 ± 1.2°

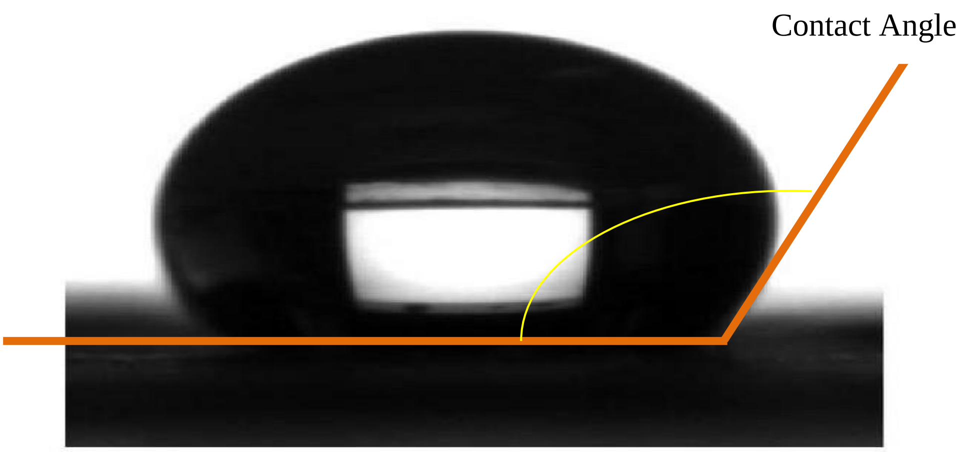

Figure A

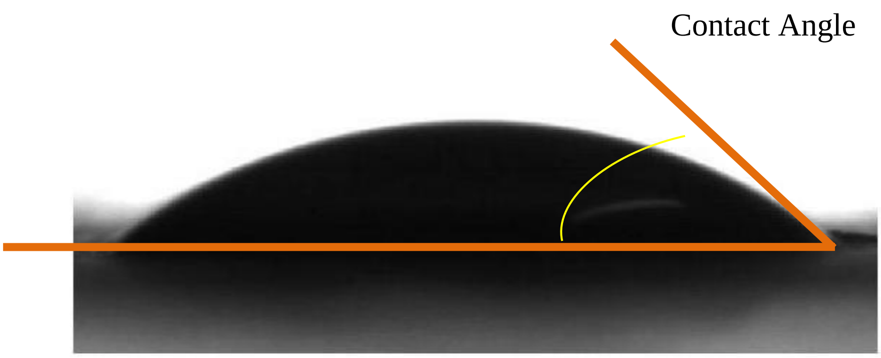

Figure B

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e) The biomechanical strengths of the two polymers, when they are used for the scaffolding around the bone structure, are:

Material	**Compressive strength (MPa)**
PCL scaffold	14 ± 1.2
PCL/PVPA scaffold	72 ± 4.9

It can be seen from the table that the PCL/PVPA polymer is around five times stronger than the PCL polymer. That feature of polymers increases their durability.

Explain why addition of PVPA to the PCL increases the compressive strength almost 5 times with the information given and pictures of the polymer's structures showed (Page 2).

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Pipe Industry

f) PVC (poly (vinyl chloride)) is commonly used polymer in the manufacture of pipes.

An estimate of how much energy (E) is contained in one photon of ultraviolet light of wavelength (λ) 300nm can be obtained using E = h x v, where h is Planck's constant (6.62 x 10^{-34} Js) and v is the frequency of radiation (c/λ), c being the velocity of light which is 3 x 10^{8} m s^{-1}. Also, the bond dissociation energy of a carbon-chlorine bond such as found in PVC (poly (vinyl chloride)) is 328 kJ mol^{-1}.

Using the information given, make the required calculations and discuss the consequences of it in terms of a lifetime guarantee.

Image 1: PVC pipes

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g) Neoprene and isoprene are two polymers often used in automotive industry. Solubility depends upon the compatibility between the chemical structures of a polymer and it's solvent. In the automotive industry neoprene (Figure 1) and isoprene (Figure 2) are used in a variety of areas.

If you were an engineer designing a car which of the two polymers shown below would you use for the fuel line which the non-polar petrol flows through, and which one would you use as the brake fluid pipe in which polar brake fluid flows? Give reasons for your choice.

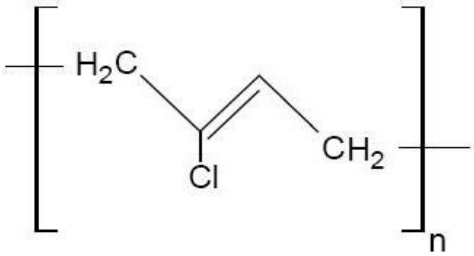

Figure 1: Neoprene

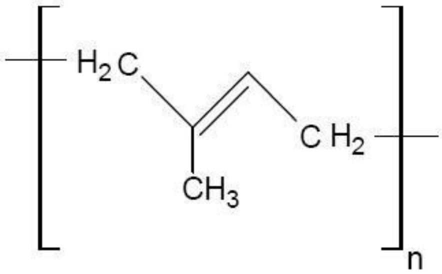

Figure 2: Isoprene

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h) Porosity and permeability are important parameters for polymers. However, the most significant feature of polymers that are used for the human body is their compatibility with the body. For instance, hard lenses are usually made from poly methyl methacrylates (Figure 3) and soft contact lenses usually employ poly hydroxyethyl methacrylate (Figure 4).

With reference to its structure explain why to use poly (hydroxyethyl methacrylate) is more suitable than poly (methyl methacrylate) for soft lenses?

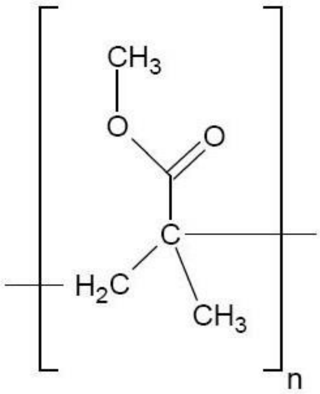

Figure 3: Poly Methyl Methacrylate

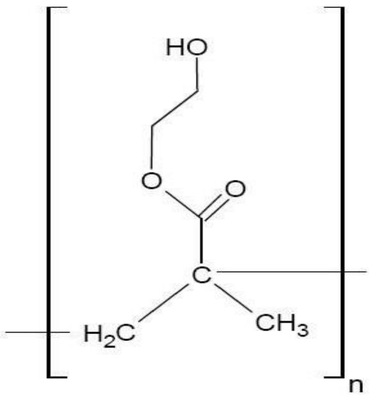

Figure 4: Poly Hyroxyethyl Methacrylate

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This is the end of this test; please use this page to write your comments about the questions.

You may write any comment about the questions, also you may like to comment on:

The difficulty level of questions,

The clarity of the questions,

Thought-provoking features of the questions,

Similarities/differences of the questions compared with exam questions,

Practical features such as time management, paper, and print qualities, colours and the available space for answers.

Any information will be useful!

Thank you very much again for your time and help.

Appendix 7

LECTURER INTERVIEW QUESTIONS

IQ1: How do you see the teaching on the Macromolecules course differ from the teaching on other courses?

IQ2: What have you liked most and what have you liked least about the individual learning approach and why?

IQ3: What were students' general reactions towards the independent learning approach?

IQ4: You facilitated tutorials for the Macromolecules course in the past as well. Have you observed any differences between students who have been taught in a traditional way and students who have been taught in the independent learning style of teaching?

IQ5: Has your way of teaching been influenced by the independent learning style of teaching?

IQ6: Would you consider preparing and leading a course using the independent learning style? Why?

IQ7: What do you think are the biggest challenges for lecturers using the independent learning style in their teaching?

IQ8: What do you think is the motivation of the course leader in designing the Macromolecules course using the independent learning style rather than a traditional teaching approach?

IQ9: What would be your advice to next year's students about the course?

IQ10: In the department of chemistry, to what extend do you think your views represent other lecturers' opinions on teaching Chemistry at university level?

Appendix 8

COURSE LEADER'S INTERVIEW QUESTIONS

IQ1: What is your motivation for designing the Macromolecules course in the independent learning style rather than a traditional teaching approach?

IQ2: In what ways has your teaching on the Macromolecules course differed from your teaching on other courses?

IQ3: What do you consider to be the main advantages and drawbacks of the individual learning approach and why?

IQ4: What were students' general reactions towards the independent learning approach?

IQ5: You facilitated the course in traditional teaching approach in the past as well. Have you observed any differences between students who have been taught in a traditional way and students who have been taught in the independent learning style of teaching in terms of student achievement and their attitudes to the course?

IQ6: Has your way of teaching in other courses been influenced by the independent learning style of teaching in the Macromolecules course?

IQ7: The learning objectives for the course include developing independent learning skills such as self-assessment, scientific reasoning and creativity. Do you think these have been achieved? Do you have any specific way of measuring those skills?

IQ8: What do you think are the biggest challenges for lecturers using the independent learning style in teaching?

IQ9: You ask students to prepare their own video material to present in the Macromolecules course. What is the importance of video material in chemistry education for you?

IQ10: What do you think of the arguments some staff might put forward that preparations of the innovative teaching styles such as the independent learning style places a much higher demand on time than a more traditional approach?

IQ11: What would be your advice to next year's students about the course?

IQ12: In the department of chemistry, to what extend do you think your views represent other lecturers' opinions on teaching chemistry at university level?

<u>Appendix 9</u>

ETHICAL ISSUES AUDIT FORM

THE UNIVERSITY *of York*

Department of Education

Ethical Issues Audit Form

This questionnaire should be completed for each research study that you carry out as part of your degree. You should discuss it fully with your supervisor, who should also sign the completed form. **You must not collect your data until you have had this form signed by your supervisor.**

Surname / family name:	CUKUROVA
First name / given name	MUTLU
Programme:	PhD in Education
Supervisor (of this research study):	Prof. Judith Bennett
Topic (or area) of the proposed research study: An investigation of the effects of a novel teaching approach at university level.	
Where the research will be conducted: The University of York, Department of Chemistry	
Methods that will be used to collect data: Diagnostic Questions, Focus Group Interviews	

To be completed by the supervisor of the research study (after reviewing the form):

Please ☑ one of the following options.

☑	I believe that this study, as planned, meets normal ethical guidelines
☐	I am unsure if this study, as planned, meets normal ethical guidelines
☐	I believe that this study, as planned, does not meet normal ethical guidelines and requires some modification.

Signed (Supervisor): Judith Bennett Date: 30 April 2012

Supervisor, please now pass to the Programme Administrator.

Or, if there are concerns, pass to the Programme Leader (or TAG member for research students).
(If the Programme Leader is the same person as the supervisor, then the Programme Director).
If these concerns cannot be resolved, then please pass to the Chair of Education Ethics Committee.

Data sources

1 Does your research involve collecting data from people, e.g. by observing or testing them, or from interviews or questionnaires. YES/NO

Note: The answer to this will normally be 'yes'. It would only be 'no', if the research was entirely based on documentary sources, or secondary data (already collected by someone else). If the answer is 'no', then please go straight to question 12.

Impact of research on the research subjects

For studies involving interviews, focus group discussions or questionnaires:

2 Is the amount of time you are asking research subjects to give reasonable? Is any disruption to their normal routines at an acceptable level? YES/NO

3 Are any of the questions to be asked, or areas to be probed, likely to cause anxiety or distress to research subjects? YES/NO

4 If the research subjects are under 16 years of age, have you taken steps to ensure that another adult is present during all interviews and focus group discussions, and that questions to be asked are appropriate? YES/NO

For studies involving an intervention (i.e. a change to normal practices made for the purposes of the research):

5 Is the extent of the change within the range of changes that teachers would normally be able to make within their own discretion? YES/NO

6 Will the change be fully discussed with those directly involved (teachers, senior school managers, pupils, parents – as appropriate)? YES/NO

Informed consent

7 Will steps be taken to inform research subjects in advance about what their participation in the research will involve? YES/NO

8 Will steps be taken to inform research subjects of the purpose of the research? YES/NO

Note: For some research studies, the data might be seriously distorted by informing research subjects in advance of the purpose of the study. If this is the case (and your answer to question 8 is therefore 'no'), please explain briefly why.

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9 Will steps be taken to inform research subjects of what will happen to the data they provide (how this will be stored, for how long, who will have access to it, how individuals' identities will be protected during this process)? (YES)/NO

10 In the case of studies involving interviews or focus groups, will steps be taken to allow research subjects to see and comment on your written record of the event? YES/(NO)

11 Who will be asked to sign a statement indicating their willingness to participate in this research? Please **tick all categories** that apply:

Category	*Tick if 'yes'*
Adult research subjects	✓
Research subjects under 16	
Teachers	✓
Parents	
Headteacher (or equivalent)	
Other (please explain)	

Reporting your research

12 In any reports that you write about your research, will you ensure that the identity of any individual research subject, or the institution which they attend or work for, cannot be deduced by a reader? (YES)/NO

If the answer to this is 'no', please explain why:

Signed: [signature]

Date: 30.04.2012

Please now give this form to your supervisor to complete the section on the first page.

NOTE ON IMPLEMENTING THE PROCEDURES APPORVED HERE:
If your plans change as you carry out the research study, you should discuss any changes you make with your supervisor. If the changes are significant, your supervisor may advise you to complete a new 'Ethical issues audit' form.

For Masters students, on submitting your Masters Dissertation to the relevant programme administrator, you will be asked to sign to indicate that your research did not deviate significantly from the procedures you have outlined above.

For MPhil/PhD students, once your data collection is over, you must write an email to your supervisor to confirm that your research did not deviate significantly from the procedures you have outlined above.

Appendix 10

CERTIFICATE OF COMPLETION FOR THE ACADEMIC INTEGRITY ONLINE TUTORIAL

THE UNIVERSITY of York

Certificate of completion

for the

Academic Integrity Online Tutorial 2012/13

Mutlu Cukurova

106030562

Date Printed: 12 October 2012

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